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KINETICS OF ALGAL SYSTEMS IN WASTE TREATMENT. FIELD STUDIES

Aaron Meron, et al

California University
Berkeley, California

May 1971

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KINETICS OF ALGAL SYSTEMS
IN WASTE TREATMENT
FIELD STUDIES
FINAL REPORT

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KINETICS OF ALGAL SYSTEMS
IN WASTE TREATMENT
FIELD STUDIES
FINAL REPORT
PART III

by

Aaron Meron
William J. Oswald
Henry K. Gee

Federal Water Quality Administration
U.S. Department of the Interior
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16. Abstract

Three domestic sewage stabilization pond systems were studied to evalute the relationship between design criteria and performance criteria for pond systems in accomplishing specific waste treatment steps. System 1 consisted of a lined high-rate pond following sedimentation, system 2 was comprised of conventional secondary waste treatment followed by a pond system, and system 3 consisted solely of several deep ponds in series. Study results indicated that system 3, consisting of an anaerobic pond, an unlined high-rate pond, and deep high-rate polishing pond, was effective in both BOD and nutrient removals, with mean annual removals of 97.3%, 93.2%, 91.6%, and 64.5% for BOD, COD, total nitrogen, and phosphate. Results confirmed that pond functioning is determined by position with respect to other ponds and unit processes, as well as their individual design characteristics. Other study results demonstrated that: (1) efficient N and P removal depends upon carbon availability; (2) high-rate ponds develop a sludge-slime bottom layer which prevents erosion; (3) proper nutrient balance, as measured by C:N and C:P is essential for effective algal growth and nutrient removal; (4) deep anaerobic ponds should be operated as an aerobic layer above an anaerobic layer; and (5) nutrient balance as well as pH can be adjusted in high rate ponds by CO_2 addition. (Lowry-Texas)

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ABSTRACT

Three novel prototype, domestic sewage stabilization pond systems were studied in order to evaluate the relationship between design criteria and performance criteria for such ponds in accomplishing specific waste treatment steps. Such a study was essential to relate fundamental experimental data from laboratory and small experimental ponds to that obtained for full-scale ponds operating under field conditions.

The first system studied was a lined high-rate pond 12 inches deep following conventional primary treatment. The second pond system studied was a pond system preceded by a conventional secondary waste treatment plant. The third system studied consisted solely of several deep ponds in series.

Study results from the first system demonstrated that, while performing satisfactorily most of the year, the system failed in summer. In summer (mean pond temperature 21.4°C, and 14 daylight hours) the producion of undesirably high pH levels that persisted throughout the day and night eventually resulted in reduced ability of the pond to grow algae, to produce oxygen or to remove nutrients in spite of its propensity to do so at other times.

The study results with the second system which consisted of an anaerobic pond, an unlined high-rate pond, and a deep high-rate polishing pond indicated that, while the system removed BOD efficiently, it was not efficient in nitrogen and phosphate removal. Reasons for poor nutrient removal were: 1) excessively short detention times; 2) a nutrient imbalance

with respect to carbon (i.e., carbon deficiency); 3) the low solids content of influent to the system; and 4) introduction of the treated sewage into the surface of the anaerobic pond rather than into the lower (anaerobic) layer. The carbon deficiency was due to the removal of BOD in the secondary treatment plant.

Study results of the third system which consisted of an anaerobic pond, an unlined high-rate pond, and a deep high-rate polishing pond, showed that while this system was effective in both BOD and nutrient removal, removal of BOD was more extensive in degree than that of nutrient removal particularly during the winter and spring. Mean annual removals in this system during the study were: BOD, 97.3%; COD, 93.2%; total nitrogen, 91.6%; and phosphate, 64.5%. Nitrogen and phosphate removals were lower than these means during winter and spring. The most likely reason for the less effective nutrient removal that occurred in winter and spring was the presence of a dense population of daphnia in the polishing pond which, in grazing on algae, thereby eliminate the algae as nutrient removers and release their nutrients. Most of the treatment in the system occurred within the first three ponds. The two polishing ponds functioned mainly as storage and percolation basins.

The study confirmed the hypothesis that the function of ponds is determined by their position with respect to other ponds and unit processes as well as their individual design characteristics. Efficient nitrogen and phosphate removal is dependent upon the availability of carbon and, hence, is best attained in ponds not preceded by carbon removal systems.

Other results of the study included 1) the finding that man-made linings are probably unnecessary in high-rate ponds because they develop a sludge-slime layer of such a nature as to protect the pond bottom from erosion; 2) the importance of nutrient balance measured by nutrient ratios such as C:N and C:P) for effective algal growth and nutrient removal; and 3) that deep anaerobic ponds should best be loaded and operated such that two distinctive layers are maintained, a lower anaerobic layer and an upper aerobic-algal layer. An anaerobic pond operated in such a manner becomes very effective in both BOD and nutrient removal without creating nuisance problems. 4) In high-rate ponds, a proper (C:N) nutrient balance can be attained by adding CO_2 which not only would serve as a carbon source but also would aid in pH control.

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I. INTRODUCTION

BACKGROUND

The first sewerage systems constructed in the second half of the nineteenth century were collection systems only, and were without any treatment facilities. After the problem of the organic load and overload they imposed on rivers became recognized, some sewage was diverted to land for agricultural use and/or treatment. As time went on and cities grew, land became scarce and what are now called conventional sewage treatment processes began to emerge. From the beginning of the twentieth century, these conventional processes developed rapidly in the United States and in some European countries. In most of these countries the industrial revolution was in progress and reliance was placed on mechanical systems dependent upon sources of power other than man. In the United States, especially, where labor costs were high, mechanization soon became almost a necessity.

With the passage of years, the treatment processes became more and more sophisticated and required expensive equipment and controls, more power, and skilled operators. Scientific understanding of the processes increased along with the development of engineering concepts until, today, plants are complicated in design, costly to construct, and complex in operation.

Acceptance of "stabilization ponds" in the late 1940's as a new treatment technique did not excite much enthusiasm. One reason for the slow acceptance of these ponds was that the equipment manufacturers and consulting engineers who had a vested interest in the development of mechanized treatment processes saw little opportunity for exploiting the stabilization pond.

However, the low installation and operating cost of pond treatment did cause it to gain in popularity and it was found to be a highly satisfactory solution for many communities which had sufficient land reserves. Soon researchers and some consulting engineers became interested and the attitude toward stabilization ponds began to change. Design and operation parameters became increasingly established on scientific principles and engineering concepts. Work with ponds revealed that these natural stabilization ponds could be incorporated into systems which were at least as scientifically complex as the conventional methods. It was also revealed that much further research was needed for an understanding of the underlying principles of waste pond ecosystems.

For many years students, professional engineers, and public officials came to the United States from developing countries to study and to inspect waste treatment methods. They usually found that most of the mechanized methods did not fit into the framework of the economy and general stage of development of their native countries. On the other hand, stabilization ponds were applicable, but the scientific principles and engineering concepts for pond design and operation were lacking. With research it rapdily became apparent that ponds may be designed to perform a wide variety of unit operations in addition to BOD removal.

RECENT DEVELOPMENTS

In recent years a growing concern for biostimulation and eutrophication of surface waters indicates that new treatment processes capable of plant nutrient removal are needed all over the world. New treatment methods designed for nutrient removal have generally involved the utilization of physical, chemical, or bacterial processes, and have been the subjects of a number of laboratory and pilot plant scale studies. On the other hand, stabilization pond systems designed for intentional growth of algae (with or without algal removal) have received little attention as nutrient removal systems.

Recent studies on the Bay-Delta Project in California (San Francisco Bay and Sacramento-Stockton region) indicate that chemical type processes remove specific nutrients whereas bacterial type processes remove nutrients mostly in a reduced and not finally mineralized stage. While both chemical and bacterial processes remove well-identified nutrients, they do not resolve the overall biostimulation problem.

At the time when waste stabilization ponds were first developed and studied, BOD and most probable number (MPN) of coliform were the primary parameters by which treatment performance could be evaluated satisfactorily. However, now that pond effluents are being proposed for use in agriculture, industry, and ground water recharge, the need has arisen for a new set of parameters capable of reflecting the higher degree of treatment required by such uses. Because of this development, previous information on pond design and performance is no longer adequate.

During the late 1960's and early 1970's, additional changes in waste water treatment and pollution control have taken place. The origins of these changes are manyfold. The complexity and quantity of new materials now being used in households, commerce, and industry have led to complications in the treatment of residues from the use of these materials, and in the means of evaluating the extent of the treatment. For example, one complication receiving increased attention is that of toxicity, especially in terms of long-range effects. Other examples are those connected with the presence of resistent substances (i.e., those unaffected by conventional treatment processes), nutrients, salts, and organic materials. Even sludges, which are by-products of the activated sludge process, are often in a colloidal state and as such are difficult to dewater and dispose of.

Because of the changing needs in sewage treatment, increasing attention is being given to treatment processes for removing nutrients, refractory substances, and other troublesome materials. Within the framework of these changing needs, many research efforts have been made and now are being directed towards the growth of algae on waste waters, as well as to relate the resulting findings to the development of pond systems. The difficulty with much of the research reported heretofore is that most of the efforts have been devoted to small laboratory reactors. Little has been done to study those few ponds which are on a practical scale and operate under natural outdoor conditions. As a consequence, while a great deal of the information available in the literature is excellent in terms of basic science, it often has only limited practical value.

Fundamental studies of complex algal bacterial ecology in stabilization ponds have been under study at the University of California Sanitary Engineering Research Laboratory, Richmond, California, for about 20 years. In recent years, the University and several engineering firms in the San Francisco Bay Region have availed themselves of this fundamental information to design and construct ponding systems to accomplish waste treatment of increasing degrees of complexity. Several such systems now exist. Among them are the plants at Richmond, Concord, and Saint Helena, California.

STUDY OBJECTIVES

From information available at the beginning of the study, it was known that stabilization ponds generally are designed on the basis of an uncertain number of criteria, and consequently are used to serve a variety of purposes, e.g., primary treatment, secondary treatment, nutrient removal, and/or a combination of these treatments. However, no systematic evaluation relating to design criteria and to pond performance has been made. Indeed, there is little evidence that design criteria and operational procedures in stabilization ponds are closely related to specific purposes and functions, as is the case in conventional treatment plants in which each treatment unit is designed to function for a specific purpose.

Consequently, there are several hypotheses among pond designers, and many times there are conflicting opinions regarding the relation of design to actual pond performance. Such controversies arise when design criteria such as the following are evaluated: 1) the allowable loadings in respect to BOD and nutrients; 2) the effectiveness of BOD removal, and indeed, whether or not BOD removal is an effective performance parameter by itself; 3) the effectiveness of algae as an agent for nutrient removal; 4) the use of lining for high-rate ponds; and 5) the location of inlet structures in anaerobic ponds at the surface or at the bottom of the ponds.

As previously mentioned, most experimental work has been done on a small scale and with limited objectives, hence the foregoing uncertainties were evidenced from the design of prototype ponds.

The conflicts in opinion and the bridging of the gap between strictly experimental ponds and full scale operational ponds can best be resolved through a study of selected existing ponds representing variations normally met in pond design. The stabilization ponds located at Richmond, Concord, and Saint Helena best meet the needs of such a study. Each is designed for purposes different from those of the other two, and also are operated differently, and yet their performance is evaluated by common criteria. Accordingly, it is the objective of this study to review the behavior of these three dissimilar functioning ponds in order to resolve conflicting designs to some degree and to cast some light on the unknowns.

CONCEPTS AND RATIONALE

Loadings. Loading (in pounds of BOD per acre per day) is an important design criterion for the first pond unit in a stabilization pond system, as well as for single stabilization ponds. In the past it has been found that loadings of stabilization ponds could be related to BOD removal, and/or relieving nuisance conditions (especially odors) in ponds, thus the reevaluation of loadings for deep anaerobic ponds (first unit in the Saint Helena pond system) becomes an important objective of the study.

The BOD Test. The rationale behind the belief that the BOD test is one of the more reliable parameters of pond performance is based on the practical fact that it has been used successfully as a parameter for the condition of streams and ponds over many decades, and, therefore, should be equally useful when applied to determine the removal rate of organic matter by stabilization pond systems, inasmuch as such a pond system is actually an engineered stream.

Algae as Agents for Nutrient Removal. In addition to removing the known and well-identified macronutrients (nitrogen and phosphate) from waters in which they are grown, algae are able to remove those micronutrients, organic and metallic, which are needed for algal metabolism. The mechanism of removal may be assimilation into the algal cell, adsorption on the cell surface, or induction through algal activity of conditions leading to formation and precipitation of insoluble inorganic complexes.

An appreciable number of nutrients are used in algal nutrition. As early as 1869 Molisch pointed out that the mineral nutrition of algae is not unlike that of higher plants. This general conclusion has been reaffirmed many times. Among major absolute requirements for algae in addition to water are carbon, nitrogen, phosphorus, sulphur, potassium, and magnesium. Iron and manganese are required in smaller amounts. Various other elements such as zinc, boron, cobalt, molybdenum, and copper may be necessary as trace elements. Three vitamins, cobalamin (B_{12}), thiamin (B_1) and biotin are also required either singly or in combination by a number of algae (1, 2).* It follows that growth and removal of algae would, as a minimum, remove those substances which are incorporated in algal cells.

Lined versus unlined high-rate ponds. Special attention was given to the problem of high-rate pond lining in this study by comparing the operational problems characteristic of the Richmond high-rate pond with those of the Concord and Saint Helena high-rate ponds which have no special lining. The principal reason usually advanced for the requirement that pond systems be lined is that inasmuch as mixing is essential for algal growth in sewage without a hard surface lining, silt and soil particles would be suspended each time the pond was mixed. The suspension of silt and soil would render the pond liquid too turbid to admit light, i.e., reduce light penetration, even to the extent that an algal crop could not be supported.

In previous research (37, 94) it was found that some mixing was essential for intensive algal growth in high-rate ponds. Inasmuch as mixing is a necessity to the sustained culture of algae, while at the same time adequate light penetration is equally important, means had to be found for mixing a pond without bringing about an objectionable degree of turbidity. One solution was to line the pond bottom. The presence of the lining obviously would prevent erosion and the suspension of bottom silt and soil when the pond was mixed.

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*Numbers in parenthesis indicate references to be found in Reference Section.

Inlet Structures for Anaerobic Ponds. In the case of inlets, the question is whether or not the incoming raw sewage should be introduced at the pond bottom as practiced in the United States or just below the surface of the pond as practiced in many other countries.

Additional Aim. An additional aim of the study was to find relatively simple analyses for stabilization ponds that could be carried out by plant operators in field laboratories. Ideally the results of such analyses should reflect overall pond conditions and should also be indicative of necessary changes in pond operations to attain desired performance.

STUDY PROCEDURES

As noted previously, three novel pond systems were investigated in this study. They included the pond system in Saint Helena where all the treatment steps are carried out in ponds, the system at the Richmond Field Station in which primary treatment is followed by a lined high-rate pond, and the system in Concord where a secondary treated sewage receives tertiary treatment in a pond system following a two-stage, high-rate biofilter.

The actual research work was begun with observations made of the high-rate pond at the Richmond Field Station by conducting two 24-hour test runs to check pond performance. The first run was made at the height of optimum growth for the Bay Area (August 20-21); and the second test run in early fall (October 20-21).

After completion of the analytical work on these two test runs, the investigation was extended to include the existing pond system of the City of Concord. The major study period for the Concord ponds extended from October 23, 1969 until December 6, 1969, but additional observations such as sludge and algal tests were continued until August 1970.

Research work involved in test runs on the two pond systems was supplemented by laboratory tests involving the use of flask cultures maintained in light boxes. The primary goal of the laboratory study was to clarify the relationship between carbon, nitrogen, and phosphorus as related to algal growth; between pH level and phosphate precipitation; as well as other phenomena related to algal growth in pond systems.

Following the summarizing of the results of the laboratory studies and of the preliminary conclusions based on the studies at Richmond and Concord, a study on the Saint Helena Pond System was initiated. Because it does not involve any conventional sewage treatment units (settling tank, trickling filters, etc.) and all treatment is carried out in a series of different types of ponds, the Saint Helena pond system was studied most extensively.

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II. REVIEW OF THE LITERATURE

FUNCTION OF STABILIZATION POND SYSTEMS

The literature is replete with evidence that modern sewage treatment practices may involve five fundamental treatment steps which can be accomplished by many types of treatment methods. They are:

1. Primary treatment - or physical separation of volatile, screenable, settleable and floatable solids.
2. Secondary treatment - or biological oxidation of carbonaceous and nitrogenous organic matter.
3. Tertiary treatment - or removal of oxidized or reduced nutrients.
4. Quaternary treatment - or removal of and/or toxic residual organic materials.
5. Quintenary treatment - or removal of salts and other inorganic matter.

Disinfection is another essential process which may be applied at any stage of the treatment process.

That many of these steps can be accomplished by stabilization pond systems or by specially designed ponds such as those for salt concentration will be evident from the following review.

Physical Separation

Physical separation may be accomplished in facultative ponds receiving raw sewage or in the first units of a pond system (6). In comparison with conventional settling tanks, ponds are able to achieve a higher degree of treatment than do settling tanks because of the relatively long detention times and large surface areas characteristic of ponds. This is true both for materials having a specific gravity either greater than water (sludges), or those lighter than water (floatables). On a pond bottom sludge accumulates over many years without need of being removed. Floatables, however, must regularly be removed at outlet structures. Such outlet structures generally are located in corners where the floatables concentrate because of wind action. A great deal of performance data for single facultative ponds can be found in the literature including those summarized by Fitzgerald and Rohlich (3), Towne and Horning (4), and others. These authors found that loading is the most important design criterion for single ponds.

Biological Treatment

The principal function of biological treatment is to reduce the BOD levels of sewage to such a degree that the treated sewage can be discharged into receiving waters without creating unacceptable oxygen deficiencies downstream. The BOD discharge requirements for treated sewage specified by most of the control agencies is in the range of 10 to 40 mg/l, depending mainly on the ratio between the amount of waste being discharged and the amount of receiving water. Unlined high-rate ponds, where three phases of biological growth exist, are well capable of achieving these levels of BOD removal. According to Gotaas (5), three phases of biological growth are involved: 1) stabilization of organic matter by bacteria suspended in the pond liquid; 2) growth of suspended algae and consequent oxygen supply to the pond liquid; and 3) stabilization of organic matter on the pond bottom, with subsequent release of nutrients. This type of BOD removal requires that BOD levels be low initially; and BOD removal at low levels is rather difficult. However, it can be accomplished very well in unlined, high-rate ponds.

Nutrient Removal

Nutrient removal, the most common objective of tertiary treatment, is a challenge to the waste water treatment profession today. Although after years of research, a wide array of physical, chemical, and biological procedures are available for nutrient removal, most are only in the developmental stage and are thought to be extremely expensive when compared with the physical and biological processes of primary and secondary treatment.

In regards to stabilization pond systems, it has been known for some time that substantial nitrogen removal rates can be accomplished in anaerobic ponds, either as individual systems or as part of a pond complex (6). Nutrient removal in shallow and lined high-rate ponds has also been envisioned. The first process is based on the control of pH and nutrient balance by the addition of CO_2. This process is now being tested on an operational scale in a demonstration project conducted by the California State Department of Water Resources at Firebaugh, California (18). There CO_2 is added into the sump of the circulation pumps to force algal growth.

The concept of the second process is to remove nitrogen and phosphate at high pH levels, which can be achieved in shallow ponds with suitable sunlight and temperature conditions. Phosphate precipitation and release (or volatilization) of ammonia from the pond surface may occur under such conditions. The addition of chemicals could further enhance precipitation in such shallow ponds. This phenomenon of self-flocculation by algae has been investigated by Moellmer (7).

In order to measure the overall nutrient content and the potential algal growth of a sample of water, Oswald and Golueke (8) devised the algal growth potential (AGP) test. AGP was defined by those authors as the dry weight of algae which will grow in a given water sample in the laboratory when no factor other than nutrient in the sample is limiting to algal growth. They pointed out that a given algal growth depends on the availability of many nutrients either individually or in combination. In the case that the ability to support algal growth is the desired characteristic under measurement, the tedium of determining the nutritional content of water through detailed analytical work is obviated through use of the AGP test.

Quartenary Treatment

For quartenary treatment the need is growing faster than the technology. It involves the removal of refractory organic compounds such as detergents, certain pesticides, petroleum residues, and, in many cases, toxic substances like heavy metals, phenols, cyanides, and exotic chemical compounds as well.

Algal systems may have considerable potential in quartenary treatment. For example, the absorption of chlorinated hydrocarbons by algae is well established. In unpublished studies at the Richmond Field Station, it has been found that both Scenedesmus and Chlorella adsorb chlorinated hydrocarbons in direct proportion to their concentrations and that the bond, although strong, is not irreversible. The chlorinated hydrocarbons can be removed from algae by repeated washing and centrifuging or by elutriation with oil followed by differential centrifugation. The above-mentioned studies showed that the uptake of chlorinated hydrocarbons by algae is adsorptive rather than assimilative. There is, therefore, the definite possibility of utilizing algae in pond systems as a method of controlling the concentration of chlorinated hydrocarbons in effluents to be discharged to the environment (9).

Recent research also indicates that algae have a tendency to concentrate or adsorb very high quantities of trace metals. A great deal has been written about the possibility of organic acids, algae, and microorganisms complexing iron, manganese, and other metals. Shapiro (1), Hutchinson (11), Wiessner (12), Fogg (13) and Ives (14) as well as Oswald and Golueke (15) have shown that algae possess a negative charge. For this reason it could well be that they exert a far greater influence on the availability of plant nutrients in lakes, streams, and ponds than has heretofore been realized. It may be that they act as flocculating agents in settling nutrients out of the water. Algae may alternately take up and release metals to the water, or possibly act as chelating agents complexing many of the metals, thus keeping them in suspension, thus profoundly influencing the food chains in the aquatic environment.

In view of the importance of algae to the basic food chain and the increasing use of organic chemicals in the environment, Levin (16) has recently pointed out that it is remarkable that so little definitive work has been done to study the interaction of specific algal species and specific environmental chemicals.

Quintenary Treatment

Quintenary treatment for such purposes as the removal of salts from brine wastes in oil fields, the brine discharged from water softening units, and the discharge of salts from processes in the heavy chemical industry, can be accomplished through precipitation and by lined evaporation ponds. Such ponds have to be constructed in almost impermeable soils to avoid pollution of groundwater with sodium, chloride or other dissolved ions. This type of pond is effective only in climates where the yearly evaporation rate is substantially greater than the yearly rainfall. Accordingly, such ponds are successfully employed in areas like Southern California (17), Israel, and Australia.

ECOLOGY OF STABILIZATION POND SYSTEMS

As demonstrated by Meiring, Shaw and Loedolff (20) in stabilization pond systems, the progressive purification from one pond to another is clearly indicated by the associated changes in microorganisms and macroorganisms. These progressive changes can be related to those found in the course of self-purification in a natural river. From this point of view, a stabilization pond system may indeed be regarded as an "engineered river."

Biological Associations in Stabilization Pond Systems

According to the classical view that water quality and the availability of food are the most important factors in determining the various biological associations present in the reaches of a polluted river and in a series of stabilization ponds, theoretically then, depending on the degree of pollution, ponds may be compared with certain defined saprobic zones in a polluted river. As described by Meiring (20), a primary stabilization pond may be said to be alphamesosaprobic (polluted), and a secondary or tertiary oxidation pond may range from betamesosaprobic (mildly polluted) to oligosaprobic (nonpolluted). As purification proceeds and as the pond liquid passes into successive ponds, different communities are successively established with each community comprising a different association.

The food chains in the ponds start with the reducing organisms feeding on the raw organic matter. The types present are determined by the chemical nature of the water. Bacteria and certain protozoa feed on the organic matter bringing about "mineralization" and making available abiotic substances such as carbon dioxide, phosphorus salts, ammonia compounds, and other nutrients to the producing organisms, the green algae in the phytoplankton and the benthos (29). The algae utilize solar energy in the process of photosynthesis and produce carbohydrates, proteins, fats and other complex materials and liberate oxygen into the water. Supplying oxygen to the pond liquid is the most important function of the algae from the purification point of view. The products of photosynthesis are needed by all organisms for energy requirements. The primary consumers (herbivores), such as crustacea and insect larvae in the zooplankton "graze" on the algae and/or bacteria (20). These organisms are filter feeders and feed by straining the water. Secondary consumers (carnivorous predators) feed on the primary consumers and they in turn fall prey to one another. Many of the algae incorporated in fecal pellets settle to the bottom, where they are eventually decomposed by bacterial action and part by the bottom organisms and scavengers. Although some are predators the bottom organisms feed mainly on detritus and attached algae. Each link in the food chain along the line of purification can develop into a specialized biological association.

The Bacterial Phase

In stabilization ponds the dominant bacterial flora generally consists of gram-negative, rod-shaped bacteria belonging to the genera Achromobacter, Pseudomonas, and Flavobacterium. Together the members of these genera constitute 90 to 95 percent of the total bacterial count (21). The physical, chemical, and metabolic requirements of this group are compatible with the environmental conditions such as temperature, variable dissolved oxygen, alkaline pH, and proteinaceous substrate found in stabilization ponds.

In general, coliform reduction in ponds parallels BOD removal (21, 28). Coliforms are removed because they are in an environment much different than the human intestine. Even if the environment were not different, it is doubtful that E. coli would be able to compete successfully with other bacterial species for the low energy value nutrients in sewage. On the other hand, because of hydraulic short circuiting of influent to effluent due to mixing, Cooper and Oswald (22, 23) point out that mere passage through a high-rate (mixed) pond has but little effect on the survival of bacteria in general, and in particular of coliforms and other enteric forms. Therefore, reductions in number that do occur within the two or three-day residence time in high-rate ponds is most likely due to natural die-away and settling of the organisms out of suspension in dead spots in the mixing pattern. For example, Cooper reports that in one experimental run, he found the coliform count in the sewage influent (settled sewage) to be 16 x 10^6 per 100 ml; in the pond, 16 x 10^5; and in the decanted effluent, 11 x 10^5. In the same run, the respective counts for Enterococci were 84 x 10^5, 24 x 10^4, and 36 x 10^3. Changes in total bacterial count was less pronounced, namely 12 x 10^9 in the decanted effluent. (Of perhaps greater public health significance is the fact that in a total of 100 isolations in a search for Salmonella, 29 gave typical Salmonella-Shigella reactions.)

Why is it Doubtful

The Algae Phase

According to Silva (24), who made a systematic study on algae growing in stabilization ponds, the algae most common in stabilization ponds are members of the genera Chlorella, Scenedesmus, Euglena, Chlamydomonas and Ankistrodesmus.

The predominance of algae in a stabilization pond system depends on an interacting complex of environmental conditions. Algal growth will be limited by nutrients present or by any physical conditions that are less than optimal. Increasing the suitability of a limiting factor whether it be solar energy, density of algae, nutrients, or temperature increases the amount of algae. In addition, and as already mentioned, higher organisms and predators influence algal predominance especially in the tertiary or quarternary ponds of a series where oxygen levels are relatively high. Cooley and Jennings (26) investigated a stabilization pond in Farmville, Virginia in regards to pond performance and predominance of alga genera; however, no correlation between the pond performance and any particular predominant genera could be found. After reviewing 16 studies on the subject, Fitzgerald (3), concluded:

> "The general data indicated that there is no correlation between which species become dominant in a pond and the geographic location of the pond; the degree of BOD loading; and the degree of pretreatment given the sewage."

This, to some extent, refutes the saprobic hypothesis of Meiring, *et al.* (20).

The Grazer Phase

Meiring (20) indicated that *Cladocera* is the most important component of the grazer phase following the bacteria and the algae in the stabilization pond food chain. The population density and the occurrence of various species of *Cladocera* are governed by many chemical and physical factors. However, little information is available concerning their limitations. It has been demonstrated that *Cladocera*, by means of their feeding mechanism, contribute towards the flocculation of suspended particulate matter, and to a certain extent to the removal of colloidal particles in the pond system. Loedolff (27) presented evidence that such animals are active both in full illumination and in total darkness.

Their activities immediately result in a reduction in turbidity of the pond liquid. However, little data on the influence of the grazer phase on pond performance are available.

ENVIRONMENTAL FACTORS

Light

Algae in stabilization ponds are photolithotrophic, that is they depend on autotrophic nutrition through photosynthesis. As pointed out by many authorities including Rabinowich (30, 31, 32), the primary source of energy for the living world is the sun. Sunlight is usually measured in Langleys (1 Langley is 1 gram calorie per cm^2). A number of factors greatly influence the quantity of sunlight available to plants, the most important being:

1) The solar constant as a function of month,

2) The absorptive effect of the atmosphere,

3) Latitude,

4) The season.

Utilizing all of the factors, W. J. Oswald prepared a table (33) entitled "Probable Values of Visible Solar Energy as a Function of Latitude and Month." This table enables one to estimate the solar energy for a certain location on the surface of the earth and has been used in that capacity in this study.

Temperature

As pointed out by Hermann (34) and Oswald (33) temperature is of paramount importance in the operation and performance of stabilization pond systems. It influences photosynthesis, respiration, methane fermentation and many other biological and chemical reactions.

Although photosynthesis will not take place in the absence of light, many of the steps in the photosynthetic process are controlled by enzymes. These enzymes are not sensitive to light, but they are sensitive to temperature. For example, the splitting of water is a light-sensitive photo-reaction that goes on in the chloroplast. The steps that follow in the reduction of carbon dioxide are, however, controlled by enzymes and are, therefore, temperature sensitive.

In stabilization ponds, optimum oxygen production is obtained at about 20°C, (35) but temperature variability is another important factor. The limiting lower and upper values for stabilization ponds appear to be about 4°C and 35°C, respectively. Methane fermentation carried out by methane bacteria is sensitive to temperature and it occurs very slowly at or below temperatures of 12°C (36). In shallow ponds, temperatures above 25°C seems to be detrimental to algal growth for several reasons, including malfunction of anaerobic fermentation (in shallow ponds), chemical precipitation, and others. Oswald (33) concluded that above 20°C, efficiency of algal cultures decreased as a result of extraneous light absorption and shortage of nutrients.

Level of pH

The activity and solubility of a wide variety of biologically and geochemically important substances are affected by pH. Hydrogen ion concentrations also exert a profound effect on the structural relations of protein molecules in protoplasm and on the activity of protein enzymes in the microbial cell (104).

The optimum pH for bacterial and algal activity in stabilization ponds has been studied by Oswald and Golueke (37) at the Richmond Field Station of the University of California, Berkeley. The optimum pH range was found to be between 7.0 and 8.5. The upper 8.5 level is more retardant for bacterial activity (38, 39) than for algal photosynthesis. Dawson, et al. (39) have found that above a pH level of 10.0, bacterial activity and CO_2 production is substantially reduced, whereas, algae continue to be active and continue to use the available CO_2. Steeman-Nielson (42) found that algae of the type commonly present in stabilization ponds could be cultured in media at pH levels within the range of 3.0 to 11.0 with no apparent effect on photosynthesis or respiration.

In the studies at the Richmond Field Station (37), it was also found that the pond depth strongly influenced pH level and the associated sewage oxidation. The results of this study illustrate well the interplay of depth time and pH and therefore, are presented in graphical form in Figure 1. It is evident from the figure that as the depth of a pond is increased, the time that it is in a pH range suitable for biological oxidation is also increased.

Solubility of Gases and Gas Exchange

Solubility of Gases. The solubility of gases in water depends on type of gas, temperature, salt concentration in water, and on the partial pressure of the gas in the atmosphere above the liquid phase. Gases such as carbon dioxide, ammonia and hydrogen sulfide which are most soluble become ionized in aqueous solution. Oxygen, nitrogen and methane are not ionized in water and are therefore less soluble.

In Table I is summarized the solubility-temperature relationship of some important gases which influence stabilization pond performance. In the table are emphasized the extreme solubility of ammonia, the high solubility of hydrogen sulfide and carbon dioxide, and the low solubilities of oxygen, nitrogen, and methane. The degree of ionization of gases in water is pH dependent, and therefore the pH of the water

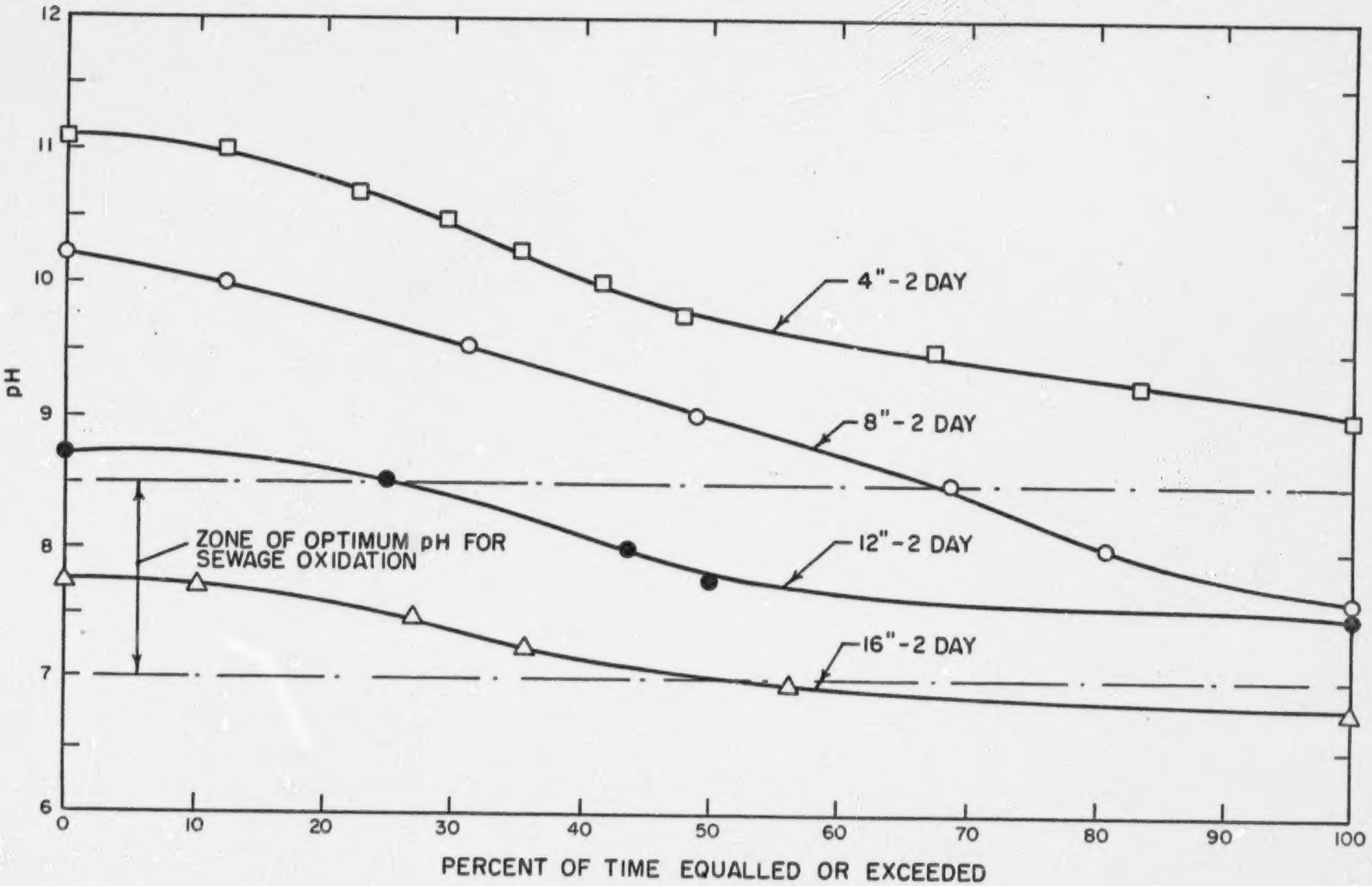

FIGURE 1.- COMPARISON OF POND pH WITH OPTIMUM pH FOR SEWAGE OXIDATION AS A FUNCTION OF OPERATING DEPTH (From reference 37)

TABLE I

SOLUBILITY OF GASES IMPORTANT IN STABILIZATION PONDS

Values in mg/l at 760 mm atmospheric pressure
from Reference (43)

Temperature °C	O_2	N_2	CH_4	CO_2	H_2S	NH_3
0	69.4	29.4	39.6	3,346	7,066	895.000
10	53.7	23.1	29.6	2,318	5,112	685.500
20	43.4	19.0	23.2	1,688	3,846	531.000
30	35.9	16.2	19.0	1,257	2,983	440.000*
40	30.8	13.9	15.9	973	2,361	

*at 28°C

water has a pronounced effect on the solubility of those gases. At this point it is worthwhile to mention that the above data are related to the solubility of gases in pure water only. Only Bronson, et al. (6) and Parker, et al. (116) reported on actual gas quantities and production in stabilization ponds. Bronson found that gas production was proportional to loading and temperature. Therefore production of the gases depends mainly on the microbiological activity of the pond. However, the behavior of gases after being produced depends on the physical and chemical characteristics of the pond liquid and the gas, and the interaction of the two has never been satisfactorily measured in ponds.

Gas Exchange. Gas exchange is still an unexplored field in stabilization pond research and very little information on the transfer of gas from the pond into the atmosphere, and vice versa, is available. This gas transfer depends not only on many physical and chemical conditions and characteristics of both the gas and the pond liquid, but also on the diurnal cycle. It has been pointed out by several authors (37, 40) that the diurnal cycle has a pronounced effect on temperature, pH, oxygen production or oxygen consumption by algae and many other important phenomena in the pond.

The theory of gas transfer is well developed, but data on the actual behavior of gas exchange (except oxygen) are limited. From the developed theories of gas transfer, it is known that the rate of molecular diffusion of a dissolved gas in a liquid is dependent on the characteristics of the gas and the liquid, the temperature, the concentration gradient and the cross-sectional area through which diffusion occurs. Many equations expressing the different phenomena in gas have been developed for the activated sludge process and can be found in the literature (41). Oswald (95) has pointed out that in most cases the net oxygen transfer in ponds is out of the water, rather than into it.

Many important phenomena relatedto gas exchange occur in a stabilization pond. These phenomena include the release of ammonia, the absorbtion of CO_2, the release and absorption of oxygen as well as the release of methane and the absorption of hydrogen sulfide. As previously stated, only meager information on the behavior of gas exchange in stabilization ponds is available, and much additional research is needed in this area.

NUTRIENT BALANCE

Composition of Algae and Nutrient Requirements

It is a well-known fact that the major constituents of algal mass like that of all living things are carbon, hydrogen, oxygen, and nitrogen. These elements comprise that portion of the total dry weight of algal solids often reported as "volatile solids" and are commonly measured experimentally as the portion volatilized by combustion at about 600°C. This portion is thus regarded as a measure of the amount of "organic matter" present in the algal solids, and normally represents 85-95% of the total dry weight of freshwater green and blue-green algae (see Tables II, III and IV).

The residue after combusion at 600°C is often termed the "ash," and contains the minor constituents (52). This portion is believed to be a good measure of the amount of inorganic material present in the algal solids. The ash normally represents 5-15% of the total dry weight of freshwater green and blue-green algae.

Using terminology analogous to that of Eyster (1), the chemical

TABLE II

CHEMICAL COMPOSITION OF SOME FRESHWATER ALGAE
(Values presented are mean values for the number of cultures indicated)

Algal Species	Number of Cultures	(% Dry Wt.) Ash	(% Ash-Free Dry Wt.) C	H	O	N	Reference
Chlorophyta							
Chlorella pyrenoidosa (sewage)	25	-	53.2	9.90	26.7	10.20	Oswald (44)
Chlorella pyrenoidosa	13	5.60	59.1	8.49	26.1	6.33	Spoehr & Milner (45)
Chlorella pyrenoidosa	18	9.45	55.1	7.69	31.1	6.07	Ketchum & Redfield (46)
Chlorella pyrenoidosa	-	-	53.0	7.50	28.5	10.80	Fogg (47)
Chlorella vulgaris	1	12.40	53.4	7.49	31.4	7.74	Ketchum & Redfield (46)
Chlorella ellipsoidea	2	8.01	47.6	7.47	36.3	8.63	Nihei, et al (48)
Stichococcus bacillaris	2	8.87	54.9	7.56	30.7	6.79	Milner (49)
Stichococcus bacillaris	6	9.61	53.8	7.09	32.5	6.62	Ketchum & Redfield (46)
Scenedesmus obliquus	2	15.38	54.7	8.18	29.0	8.08	Ketchum & Redfield (46)
Scenedesmus basilensis	1	14.34	54.8	8.32	28.4	8.46	Ketchum & Redfield (46)
Chlamydomonas sp.	1	4.74	47.5	6.82	39.9	5.81	Milner (49)
Cyanophyta							
Anabaenopsis sp.	1	9.35	49.6	7.00	35.1	7.28	Milner (49)

*For comparison: All others cited here grown on inorganic media with bubbling carbon dioxide.

TABLE III

CHEMICAL COMPOSITION OF *Chlorella pyrenoidosa* GROWN UNDER VARIOUS ENVIRONMENTAL CONDITIONS

(Based on data from Spoehr and Milner(45))

Culture	(% Dry Wt.) Ash	C	H	O	N	Protein	Carbohydrate	Lipid
1	3.45	49.5	6.78	34.4	9.31	58.0	37.5	4.5
2	3.78	51.0	6.90	30.8	11.29	70.5	23.8	5.7
3	20.21	51.6	7.37	26.9	14.11	88.2	6.6	5.2
4	5.81	54.6	7.28	27.7	10.38	64.8	17.7	17.5
5	8.56	54.8	7.93	32.0	5.28	33.0	38.2	28.8
6	7.88	54.6	8.11	26.6	10.75	67.2	11.4	21.6
7	2.28	56.0	7.84	28.3	7.86	49.2	23.0	27.8
8	2.87	59.7	8.56	26.9	4.80	30.0	24.8	45.2
9	1.36	63.8	8.97	24.2	3.08	19.2	20.8	60.0
10	5.32	65.4	9.68	23.3	1.62	10.1	20.0	69.9
11	4.57	68.2	10.01	20.5	1.28	8.0	13.2	78.8
12	3.44	69.2	10.33	19.3	1.17	7.3	9.5	83.2
13	3.46	70.2	10.53	17.9	1.43	8.9	4.8	86.3
Mean % Ash-Free Dry Weight	5.60	59.10	8.49	26.10	6.33	39.6	19.3	41.1
Mean % of Total Dry Weight	5.60	56.40	8.00	24.80	6.00	37.5	18.3	39.0

TABLE IV

RANGES OF CONCENTRATIONS OF MINOR CHEMICAL CONSTITUENTS IN *Chlorella pyrenoidosa* CELLS

Constituent	(% of Total Dry Wt.) Concentration Range	Reference
Total Ash	5.12-8.66	Scott (50)
P	0.94-1.51	"
Ca	0.00-1.55	"
Mg	0.26-1.50	"
K	0.04-1.43	"
Na	0.07-0.70	"
P	1.35-2.76	Knauss & Porter (51)
S	0.42-0.77	"
Ca	0.01-0.40	"
Fe	0.02-3.45	"
Mn	0.02-2.60	"
Sr	0.0004-0.051	"
Cu	0.0008-0.034	"
Zn	0.0004-0.009	"
Total Ash	10.50-14.32	Ketchum & Redfield (46)
P	2.43-3.01	"
Total Ash	1.36-20.21	Spoehr & Milner (45)

elements which comprise this group can qualitatively be termed as macroelements or microelements generally are present in the structural materials, whereas the microelements are commonly metal constituents of enzymes and coenzymes (55). In addition to water, macroelements commonly present in green and blue-green algae are nitrogen, phosphorus, sulfur, potassium, magnesium, calcium, and sodium. Microelements often present are iron, manganese, copper, zinc, molybdenum, vanadium, boron, chlorine, cobalt, and silicon (silicon is a macroelement in diatoms). Little is known at present as to the significance of most of the minor constituents except phosphorus.

An example of the normal or average requirements for Chlorella are those as given by Round (105). According to him, for every 100 parts by weight of carbon, about the following amounts of other major nutrients are required: N-15, P-5, Mg-2.5, K-1.8, S-1.6. Studies by Porcella (54) indicate that the composition of algae changes in accordance with the availability of nutrients in the environment. He found ratios of 1:30 (minimum to maximum) for phosphorus and ratios of 1:5 for nitrogen. If carbon, nitrogen, or phosphorus are in excess in the environment, algae may store them as carbohydrates and lipids (C), as proteins (N), or as polyphosphates (P). Some of these variations for carbohydrates, lipids and proteins are given in Table III.

Based on the data in Tables II, III and IV, a range of carbon, nitrogen, and phosphate in the composition of algae may be summarized in idealized form on the basis of dry weight. The resulting range in order of nutrient ratios is given in Table V. This range between low and high nutrient ratios may be considered as a guideline and/or first

TABLE V

Idealized Range of Carbon, Nitrogen and Phosphate in the Composition of Algae

Range	Carbon	Nitrogen	Phosphate	C/N	C/P*	N/P*
Low	100	25	5	4.0	20.0	2.5
Average	100	12	2.5	8.3	40.0	4.8
High	100	5	0.2	20.0	500.0	25.0

*In this table and in the remaining tables and text, refers to phosphorus as phosphate.

approximation of the nutrient requirements for algae in a stabilization pond. It is believed by the writer of this dissertation that if an analysis of pond liquid indicates that the C/N, C/P and N/P ratios fall within the high-low range, the ratio may be regarded as normal for algal growth in ponds, and if ratios are smaller or larger, they may be regarded as unfavorable to algal growth in ponds.

Comparative Composition of Algae and Bacteria

It is interesting to compare the composition of algae and bacteria. Two reference examples of bacterial composition are given in Table VI, together with several referenced algal compositions. As indicated by the data in Table VI, basically, the composition of bacteria and algae in regards to carbon, nitrogen, and phosphate are very similar. Bacteria metabolize these nutrients in an organic form, converting them to simple oxides which are utilized by algae. Algae then metabolize elements in a mineralized form.

Hoover and Porges (56) have analyzed activated sludge for carbon, hydrogen, oxygen, nitrogen and ash. On the basis of their analyses, they calculated an empirical formula of $C_5H_7NO_2$. Helmers, et al. (57) shows a mean of 1.2% of phosphorus and 8.8% for nitrogen in activated sludge. Using these values as a basis of calculation, the empirical formula $C_{118}H_{170}O_{51}N_{17}P$ is indicated. If phosphorus is ignored, a formula of $C_7H_{10}NO_3$ is obtained. Because of the wide variation of nitrogen in the activated sludges reported by Helmers (57) it does not seem reasonable to formulate a definite empirical formula for the bacteria which compose the activated sludge. This attitude is in keeping with Porcella's conclusion that algae have a variable composition (54).

TABLE VI

Composition of Algae and Bacteria
(Values in percent of total dry weight)

	Reference	C	H	O	N	P
Algae	25	52.6	7.0	28.1	12.3	
Algae	13	53.0	7.6	28.5	10.9	
Chlorella	45	56.4	8.0	24.8	6.01	
Chlorella	51					2.05
Chlorella	46					2.72
Bacteria	56	53.2	6.2	28.4	12.4	
Bacteria	57	53.0	6.4	30.6	8.8	1.2

Composition of Domestic Sewage

In the literature on sewage treatment, BOD is reported instead of carbon, and BOD/N and BOD/P ratios are used instead of C/N and C/P ratios. These BOD/N and BOD/P ratios are used by many authors to describe nutrient balances for industrial wastes and for microbial nutrient requirement (66).

To overcome the differences resulting from expressing the carbon content of sewage by means of BOD and COD only, and to bring the composition of sewage in context with all other data in this study analyzed and reported as carbon, complete analyses of the influents (raw sewage) of the stabilization pond systems studied have been made. This analysis includes T-C (total carbon), BOD, COD, total nitrogen and phosphate. The analyzed data are given in Tables XLIII and XLIV and will be discussed in greater detail in Chapter V. At this point it will suffice to state that low and unfavorable nutrient ratios have been found in the domestic raw sewage analyzed.

In line with the data given in Table XLIII, the data published by the AWWA Task Group 2610P for nitrogen and phosphorus concentrations in municipal discharges (58) are worth mentioning. The latter data indicate that the usual concentrations of nitrogen and phosphorus in effluent discharges (not raw sewage influents) are in the range of 18 to 20 mg/1 for nitrogen and 3.5 to 9.0 mg/1 for phosphorus.

Nutrient Requirements

While carbon as a limiting nutrient for algal growth received attention only in recent years and is reflected in the literature of Kunentzel (59), Lange (60) and Legge (61), nitrogen and phosphorus on the other hand have long received attention. Many reasons can be cited why so much attention has been given to the stimulation effect of nitrogen and phosphate on algal growth. Four of them are:

1) From agriculture or any other type of plant growth experience, nitrogen and phosphate have to be supplied to the soil; but (as is often forgotten) CO_2 is naturally supplied by the air.

2) Natural waters generally contain small amounts of nitrogen and phosphate, but have large reserves of inorganic carbon in the form of alkalinity. If treated sewage, having most of its carbon removed (as BOD) is discharged into such natural waters, nitrogen and phosphate content has a biostimulator effect. Oswald (114), for example, found that the AGP in the Napa River, downstream from the discharge of Napa's treatment plant, to be in the range of 120 to 1270 mg/l, whereas the AGP of natural waters is in the range of 10 to 20 mg/l.

On the other hand, sewage and pond liquids are eutrophic in character and contain relatively large amounts of nitrogen and phosphates and small amounts of carbon. Carbon deficiencies are, therefore, found in pond liquids (3).

3) There has been widespread dependence on Sawyer's statement (62) that "nuisance conditions can be expected when the concentration of inorganic phosphorus exceeds or equals 0.01 ppm." As is evident from the work of Zabat (63), this concentration of phosphate would support from 1 to 2.5 mg per liter of algae before phosphate itself became limiting. This quantity of algae turns water visibly green and therefore could be regarded as a nuisance. However, application of the algal growth potential tests, for example, indicate that it is incorrect to assume that phosphate alone is responsible for eutrophication. The lack of understanding in regards to the dependence of algae growth on many nutrients, on various nutrient combinations, and on nutrient balances as well as imbalances led to many misinterpretations of Sawyer's observations.

4) In almost all laboratory experiments where algae are grown, air

or CO_2 enriched air is bubbled through the growing media for mixing and/or pH control without considering the nutrient effect of CO_2 as carbon or the secondary effects of CO_2 on the solubility of other substances such as trace minerals.

In order to have a better understanding of the problems connected with the nutrient balances in stabilization pond systems, it is worthwhile to introduce related nutrient data from other areas which have a longer history of nutritional research, namely 1) plant growth under agricultural cultivation methods; 2) composting, and 3) nutrient requirements in the activated sludge processes, will be described in the following paragraphs.

Cultivated Agriculture

Under agricultural cultivation methods, plant growth depends on the seasonal cycle, and is strongly influenced by local weather conditions. However, as a result of decades of intensive research, agriculture crops may be given all the necessary nutrients in a "balanced diet" which has been scientifically established (64). The two basic factors for this "balanced diet" are the needs of the plant, and the availability of these nutrients in the soil, in the water, and in the air.

Usually, the two most important nutrients supplied are nitrogen and phosphate. Carbon is absorbed from the air (CO_2) through microscopic openings (stomata) in the plant leaf. The magnitude of the gas exchange through the stomata is indicated by the fact that in one hour a growing leaf may absorb an amount of CO_2 equivalent to that in a six-foot column of air upon its surface (112). Multiplying this by the number of leaves on a tree, the figure becomes truly impressive. Also, watering and cultivation increases aerobic bacterial activity in the soil, hence releasing CO_2 into the air near the plant. Thus, it can be seen that carbon supply to terrestrial plants is not a problem, but the carbon supply to algae in and within the pond liquid is believed to be a critical problem particularly for algae in domestic waste disposal ponds.

Composting

Studies have shown that the C/N ratio is an important parameter for the evaluation of materials for the composting process (65). It has been found that the best suited C/N ratio for composting is in the range of 30 to 35, i.e., 30 or 35 times as much carbon as nitrogen is needed for successful composting operations. For example, solid wastes containing great amounts of cardboard and/or paper (high in carbohydrates) have C/N ratios of 70 and more. In such cases, decomposition is slow and the available nitrogen has to be recycled several times through microorganisms (bacteria and fungi) until the composting process has been completed. This may require 20-30 or more days. On the other hand, if solid wastes have a C/N ratio near 30, they can be decomposed within 12 to 15 days. Thus, if the C/N ratio is low, as in agricultural wastes (raw manure for example), the composting process progresses rapidly but great amounts of ammonia are lost to the atmosphere. This ammonia loss causes odors and degrades the end-product for agricultural use.

The Activated Sludge Process

This process is to a great degree similar to the high-rate pond process, but here bacterial growth is emphasized with the main objective of carbon removal expressed as BOD removal. Regarding the nutrient supply for the bacteria, to quote Sawyer (66):

> "Nutrition and synthesis are intimately related factors. Synthesis and growth are essentially synonymous terms. Growth results from the marshalling of part of the food supply and accessory mineral factors to produce new generations of the organisms with characteristics and chemical composition similar to the progenitors. A

considerable fraction of the food is used for energy purposes. Growth or synthesis can be predicted from the 5-day BOD of a waste. About 0.5 lb. of new growth will occur for each lb. of BOD stabilized, regardless of temperature or aeration solids."

In the activated sludge process the emphasis also is given to a balanced nutrient supply. (The desired BOD/N ratio as given by Sawyer is 17:1 to 32:1 and the desired BOD/P ratio, 90:1 to 150:1 (66). In addition, it should be mentioned that to attain effective treatment, nitrogen and phosphate are added to paper mill waste and certain other industrial wastes when they are known to be high in carbohydrates and low in proteins and phosphate compounds. At this point, it should be indicated that in the activated sludge process, extensive mixing and aeration are no substitute for a "balanced nutrition."

THEORETICAL CONSIDERATIONS

Presently emphasis is being placed on the need for theoretical-mathematical models to describe the growth and action of microbial systems. Among the models which are widely used are Michaelis-Menten (71), and Monod (72), but somewhat neglected is that of Mitscherlich and Baule (67, 68).

The Mitscherlich Limiting Factor Equation

The Mitscherlich limiting factor equation was first published by Mitscherlich in 1909 (67) and further developed by Baule (68). This limiting factor equation has not been used by scientists in the English-speaking countries. It states that:

$$E = E\ \max\ (1 - e^{-0.7x/h})\ (1 - e^{-0.7y/h})\ (1 - e^{-0.7z/h})\ (\_\_\_)\ (\_\_\_)\ (\text{etc.}) \qquad (2\text{-}1$$

where E is the rate of a process, E max is its rate if all factors (x, y, z, etc.) are present in abundance, and the $0.72/h$ factor is introduced to facilitate computation; e is the base of natural logarithms.

In order to understand the development and the discussions of the Mitscherlich equation at the time of its development, a translation of a portion of Baule's original publication (68) is given in the following paragraphs.

> "Until recently, no one questioned the absolute correctness of Liebig 's Law. Nevertheless, it has been found incorrect. In accordance with Liebig's Law, a plant adsorbs nutrients only under a specific saturation relationship. Such a law made much sense and was therefore unchallenged for a long time.
>
> However, in accordance with the scientific experiments on plant nutrition which have been carried out by Mitscherlich, a new law, namely, the Mitscherlich Law has been established. This mitscherlich Law for the physiological relationship is not, as assumed at first glance, a change or a refinement of the Liebig Law; on the contrary, it is in complete opposition to the Liebig Law. The Liebig Law is based on the specific relationship in which the action of every one of the nutrients is related to all other nutrients present. The Mitscherlich Law states that every nutrient promotes the growth of plants without any relationship to each other. This, as has already been mentioned, is in opposition to the Liebig Law in which a plant can only use the nutrient in a precise saturation relationship. However, it should also be mentioned that the Mitscherlich Law is only true when the nutrients do not interact with one another, and when no change in the soil composition occurs."

In order to explain the difference between the Liebig Law, and the Mitscherlich Law, five factors affecting growth are illustrated in the following diagram. According to Liebig's Law, only an increase in the smallest factor "A" will cause an increase in the yield of a crop. According to Mitscherlich's Law, however, an increase in any one factor (from A to E) will cause an increase in yield. A unit increase in "A" will have the greatest effect, a unit increase in "B", the next greatest effect, and so on. Factor E is so close to its maximum that any unit increase will have an almost neglible influence on yield.

Meyer (69) who discussed the Liebig and the Mitscherlich laws in his text on Plant Physiology summarized the discussion with the following remarks: "Mitscherlich's interpretation of the law of the minimum seems to be more nearly in accord with the results obtained in experiments on plants than Liebig's simple formulation of this same principle."

Since 1909 when Mitscherlich proposed his law, researchers modified his formulation and introduced different constants according to the results of their experiments. Verduin (70), for example, modified the limiting factor equation to a model of primary production in aquatic habitats:

$$Y = Y\text{ opt. } (1 - 2^{-x})\ (1 - 2^{-y})\ (1 - 2^{-z})\ (\underline{\quad})\ (\underline{\quad})\ \text{(etc.)} \qquad (2\text{-}2)$$

where Y is the photosynthetic yield, Y opt. is the yield obtainable if all factors are present at optimal intensity, and 2 is substituted for "e" (Verduin states that z is not less natural than "e" and facilitates computations), x, y, z, are the factors influencing the photosynthetic process. In the Verduin term $(1 - 2^{-x})$, x is the intensity factor; when this factor is in unity, the term becomes 0.5.

To summarize, the Mitscherlich equation indicates that several factors can be limiting simultaneously. Indeed, it seems likely that this may be the case in the process of photosynthesis in aquatic habitats such as waste ponds. There macronutrients, micronutrients, light, and the density of the algae population are often all present in suboptimal

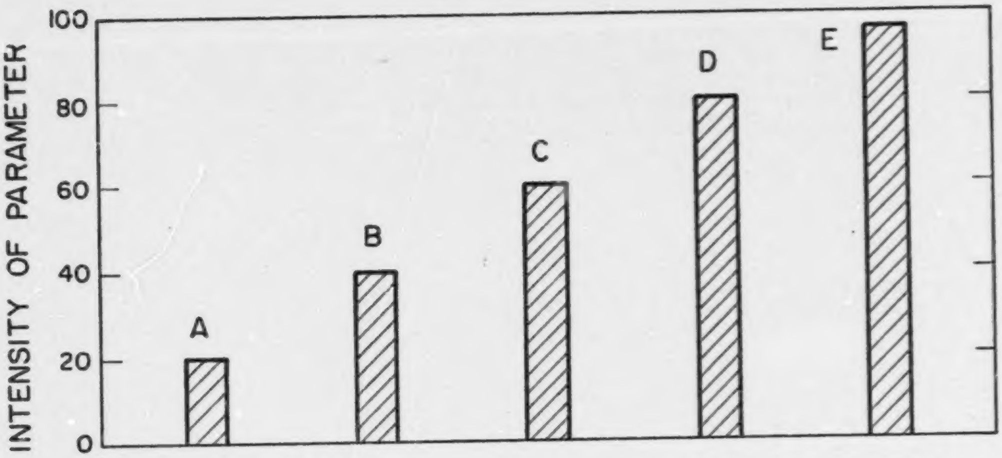

FIGURE 1A. GRAPHIC INTERPRETATION OF THE LAW OF THE MINIMUM

concentrations, and the actual photosynthetic yield is probably only a few percent of the rate that could be realized if all factors were supplied at optimal intensities. The point is then that simplified models such as Michaelis-Menten which assume only one limiting factor are probably not applicable to natural pond systems. However, more complex models have not been examined although some evidence is available. For example, as previously stated, the multiple limiting approach formulated by Mitscherlich has been tested on terrestrial plants, but little literature is available on the multiple limiting nutrient approach in natural waters or stabilization ponds. Eyster (77) indicated that iron and phosphorus have both been shown to stimulate growth of a test algae in water samples of a marl lake, and Porcella (78) stated that several nutrients will limit growth at the same time in most water samples because the concentrations of nutrients will be at levels that are equivalently related to growth.

Another approach to the problem would be to consider that various growth factors would be limiting through the lifetime of algae in stabilization ponds or during the detention time of a stabilization pond system. This means that light, temperature, macro and micronutrients may alternately be limiting during each day and during generation time of algae (two to three diurnal cycles) and that the degree of limitation may increase during the whole detention time of a stabilization pond system.

The Michaelis-Menten Equation as Modified by Monod

The Michaelis-Menten equation was introduced by Michaelis and Menten in 1913 (71) to describe basic enzyme substrate removal kinetics:

$$\mu = \frac{\hat{\mu}\,(S)}{K_s + (S)} \qquad (2\text{-}3)$$

where μ is the growth rate, $\hat{\mu}$ the maximum growth rate, S, substrate concentrations, and K_s, a specific substrate concentration at $\frac{\hat{\mu}}{2}$.

Today, single enzymatic reaction rates are determined by this equation in biochemistry and related fields. It should be noted that several enzymatic chain reaction steps are included in this equation, but the slowest step determines the speed (the enzyme substrate affinity) of the reaction. Monod (72) used equation (2-3) for a complete cell or a one-cell organism. His reasoning was that the growth rate of a cell is also determined by the slowest enzymatic reaction within the whole cell complex.

In such a capacity, this equation was used by Stewart (73) and Agardy (74) to describe enzyme substrate reactions for sewage treatment systems. Shelef (53) modified the equation to include light intensity:

$$\mu(I) = \frac{\hat{\mu}(I) \times 1}{K_I + 1} \qquad (2\text{-}4)$$

The symbols in this equation (2-4) are the same as those in equation (2-3), and I is the light intensity in cal/cm^2. A further improvement in such models has been made by Middlebrooks and Porcella (76), which includes both light and temperature in a Michaelis-Menten type of equation.

In regard to algal growth, all the above equations have been tested under controlled laboratory conditions where steady state conditions could be maintained. Applied to strictly controlled outdoor tanks in the Lake Tahoe Study, equation (2-3) has been used with some degree of success. However, as pointed out by Middlebrooks (76), additional studies (over a several-year period) will be necessary to make additional measurements with substrate dilutions, and to derive sufficient "points" for the equation.

Summary

In summary it may be said that the Verduin equation (2-2) or any other modification of the basic Mitscherlich equation (2-1) seems to have advantages over the single unit type equation of the Michaelis-Menten form, especially when used in natural outdoor conditions. The advantage of the Mitscherlich equation (2-1) then could appear to be its flexibility to consider several variables. It also makes it feasible to evaluate each environmental factor by itself, which could simplify studies under changing outdoor conditions. Nevertheless, in the study reported herein, in spite of several attempts, neither the Michaelis-Menten nor the Mitscherlich equations could be used. It was found that much more research, data, and control and monitoring equipment would have been needed to measure variables because the steady state conditions essential for testing models are practically nonexistent in outdoor ponds. However, should steady state conditions ever be established in a real outdoor pond, the Mitscherlich equation would seem to be more valuable than the Michaelis-Menten equation to describe its activities because with it one may deal with multiple variables in the same equation.

SLUDGE ACCUMULATION

Judging from the literature, sludge accumulates in stabilization ponds at a rate depending upon BOD, total and volatile solids concentration, and on the age of the pond (79, 80, 81 82). Different calculations have been tried and an accumulation rate of approximately one foot per 135 years has been predicted for the organic portion of the sludge in a 10-acre primary pond serving a population of 1,000. However, silting by inorganic materials (fixed solids) results in a faster accumulation rate. It is estimated to be in the range of one foot in 25 years.

Middlebrooks (84) derived a sludge accumulation equation from an extensive sludge study on 15 ponds in Mississippi. His equation is given as follows:

$$Y = 0.861 + 0.0404X_1 - 0.000175X_2 - 0.00289X_3 + 0.0059X_4 \quad (2\text{-}5)$$

where Y = the average sludge depth in inches

X_1 = the age of the lagoon in months

X_2 = the age of the lagoon in months multiplied by the average total solids in percent

X_3 = the BOD loading rates multiplied by the average total solids in percent

X_4 = the average total solids in percent multiplied by the average volatile solids in percent

Substituting the experimental values of the average percent of total and volatile solids as found in his study (9.25% total solids of which 24.7% were volatile), and selecting an average BOD loading value of 35 lb/acre/day, equation (2-5) reduces to:

$$Y = 0.0609 + 0.03607X_1 \quad (2\text{-}6)$$

As previously stated, this formula was developed from a study of 15 facultative stabilization ponds which receive raw sewage and experience BOD loadings in the range of 7.5 to 7.0 lb/acre/day. In more advanced units of a stabilization pond system already receiving treated sewage, the sludge accumulation will be less, but no data are available except for the first unit receiving raw sewage.

TYPICAL FIELD STUDIES OF STABILIZATION PONDS

Because stabilization ponds have been used and studied for many years, there are numerous studies reported in the literature. A complete review of all of these studies would fill many volumes but would be needlessly repetitious since only a few of the studies could be regarded as systems typical of all others, i.e., classical. For this reason, only two typical studies are described in greater detail herein. A review of these studies will also provide the reader with an overall view of the function and performance of stabilization pond systems of classical design.

The Melbourne System in Australia

The stabilization pond system 145 W in Melbourne receives raw sewage which flows through eight ponds in series. The first two ponds are anaerobic and the following six, aerobic. Parker (85) (116) describes this system with emphasis on the coliform and bacteria reduction, but information on BOD, nitrogen, algae and other pond liquid characteristics were reported and are summarized in Figure 2.

The pond system may be divided into three major units: 1) the first two ponds (sampling points 1 and 2) are anaerobic and are therefore called the bacterial unit. This unit has an 8-day detention time; 2) the third and fourth ponds with a detention time of 10 days (sampling points 3 and 4) will be called the algae unit; 3) the last four ponds with 20.5 days detention time are polishing ponds with a growing crustacea population (sampling points 5, 6, 7, and 8).

The first unit (two anaerobic ponds) was characterized by a 91.0% BOD removal (from 521 to 46 mg/1). However, the ammonia and total nitrogen concentrations showed increases of 32.4 to 52.5 mg/1, and 58.7 to 67.0 mg/1 respectively. Parker states that the ammonia increase was due to proteolysis occurring in the anaerobic ponds. No description is given for the inlet arrangements and/or the pond depth, but from the recorded algae concentrations in the first two ponds, it is assumed that a shallow algae layer covered the surface.

The algae unit (third and fourth ponds) was characterized by high

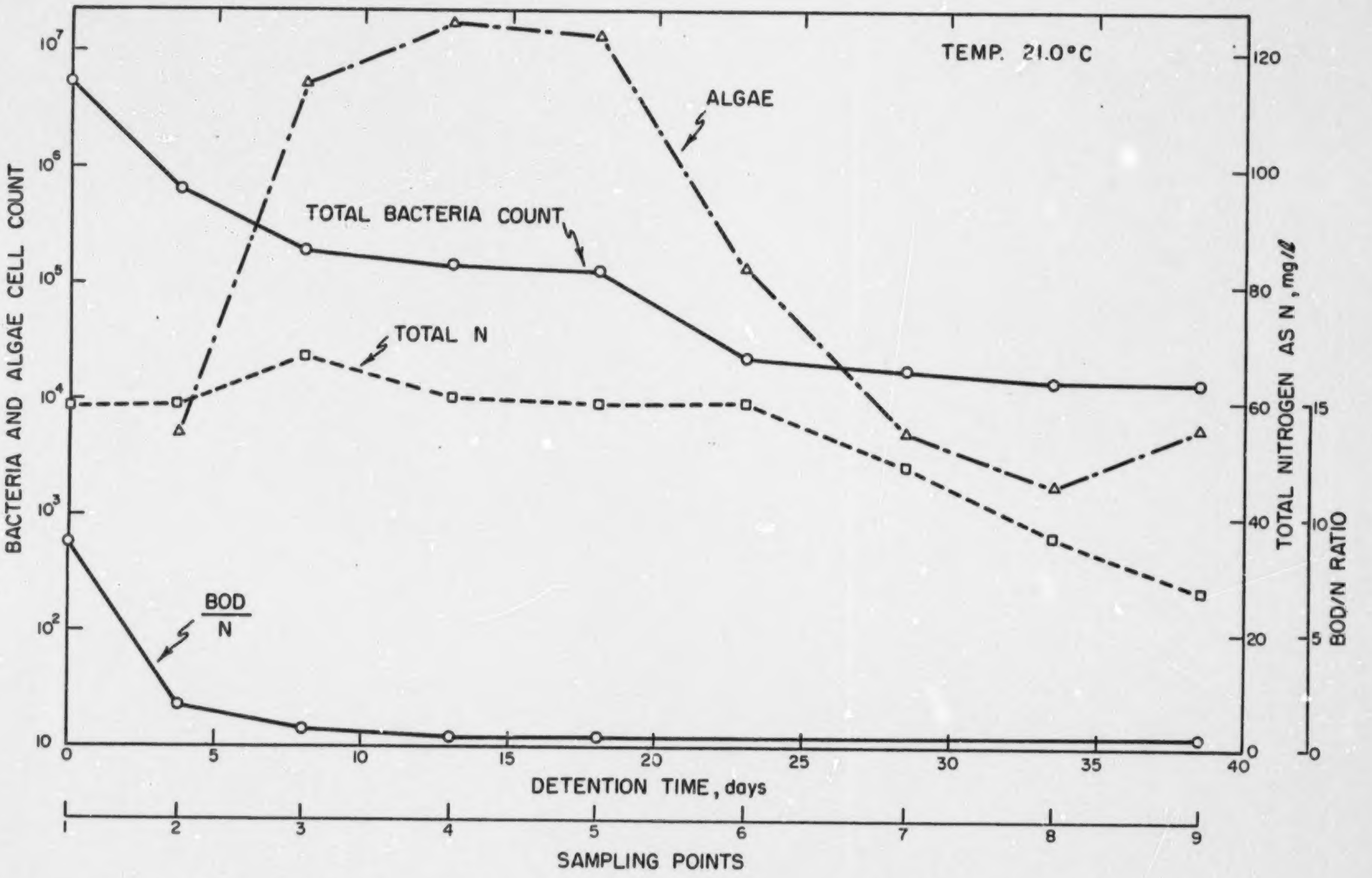

FIGURE 2. - CHARACTERISTICS OF 145W LAGOON - MELBOURNE, AUSTRALIA

algae concentrations, diminishing BOD removal, and a slight reduction in ammonia and total nitrogen. The BOD reduction was only 23.3 mg/1, or 4.5% of the influent level. The total nitrogen reduction was from 67.0 to 58.7 mg/1 and the ammonia reduction from 52.5 to 45.0 mg/1.

The last four ponds which have been termed the polishing unit is characterized by increasing numbers of grazing organisms, mostly crustacea. A change in bacterial population was also noted. BOD reduction was low, but total nitrogen and ammonia concentrations began to decrease. Total nitrogen decreased from 58.7 to 26.4 mg/1 and ammonia from 45.0 to 18.9 mg/1.

Nitrate and nitrite were first detected in the third pond after 13 days of detention time and increased to a combined concentration of 1.45 mg/1 in the effluent.

The changing nutrient balance throughout the pond system is indicated by the BOD/N ratio (cf. Figure 2) which declines sharply in the first two ponds, and is almost stable thereafter.

The Herzliya System in Israel

The Herzliya stabilization pond system consists of four ponds in series with a total detention time of 26.0 days. The first pond receives raw sewage and the treated effluent is used for ground water discharge (28, 86). Like the Melbourne stabilization pond system, the Herzliya system may be divided into three basic units. The first pond is representative of an anaerobic bacterial unit. The pond is actually facultative with heavy sludge accumulations. Consequently, during the night and early daylight hours, anaerobic conditions existed. The second pond represents the algal unit, and the third and fourth ponds may be considered to be the polishing units.

As seen from Figure 3, most of the biological and chemical changes take place in the first two ponds where bacterial and algal activity is intense. In the last two ponds, these changes are less pronounced.

A reduction of BOD from 285 to 78 mg/l (72.5 percent) has been observed in the first pond. In this pond, the alkalinity, hardness, and number of coliform bacteria (measured as MPN) were also reduced substantially. On the other hand, the algae concentration increased and the mean pH level increased from 7.5 in the raw sewage to 8.0 at sampling point 2.

The second pond was characterized by high algae concentrations, a further reduction in alkalinity and hardness, and a somewhat smaller reduction in MPN. There was still a rise in the mean pH level from 8.0 to 8.1. In the third pond, after 13 days detention time, the algae concentration declined sharply and crustacea appeared. The number of coliform organisms (MPN) still declined, but the decline in the other characteristics previously mentioned was slight. In the fourth pond, a general leveling off and slow down of microbial activity and related chemical changes occurred.

The total nitrogen concentration was reduced from 76.4 mg/l in the influent to 47.1 mg/l in the effluent, i.e., an overall reduction of 38.4 percent. Total phosphorus concentrations declined from 10.4 mg/l in the influent to 8.3 mg/l in the effluent resulting in an overall reduction of only 20 percent. The change in nutrient balance expressed by the BOD/N ratio declined from 3.7/1 at sampling point 1 to 1.23/1 at sampling point 2, and to 0.79/1 at sampling point 5. This change indicates that carbonaceous substances decline in relation to nitrogen. A greater change for

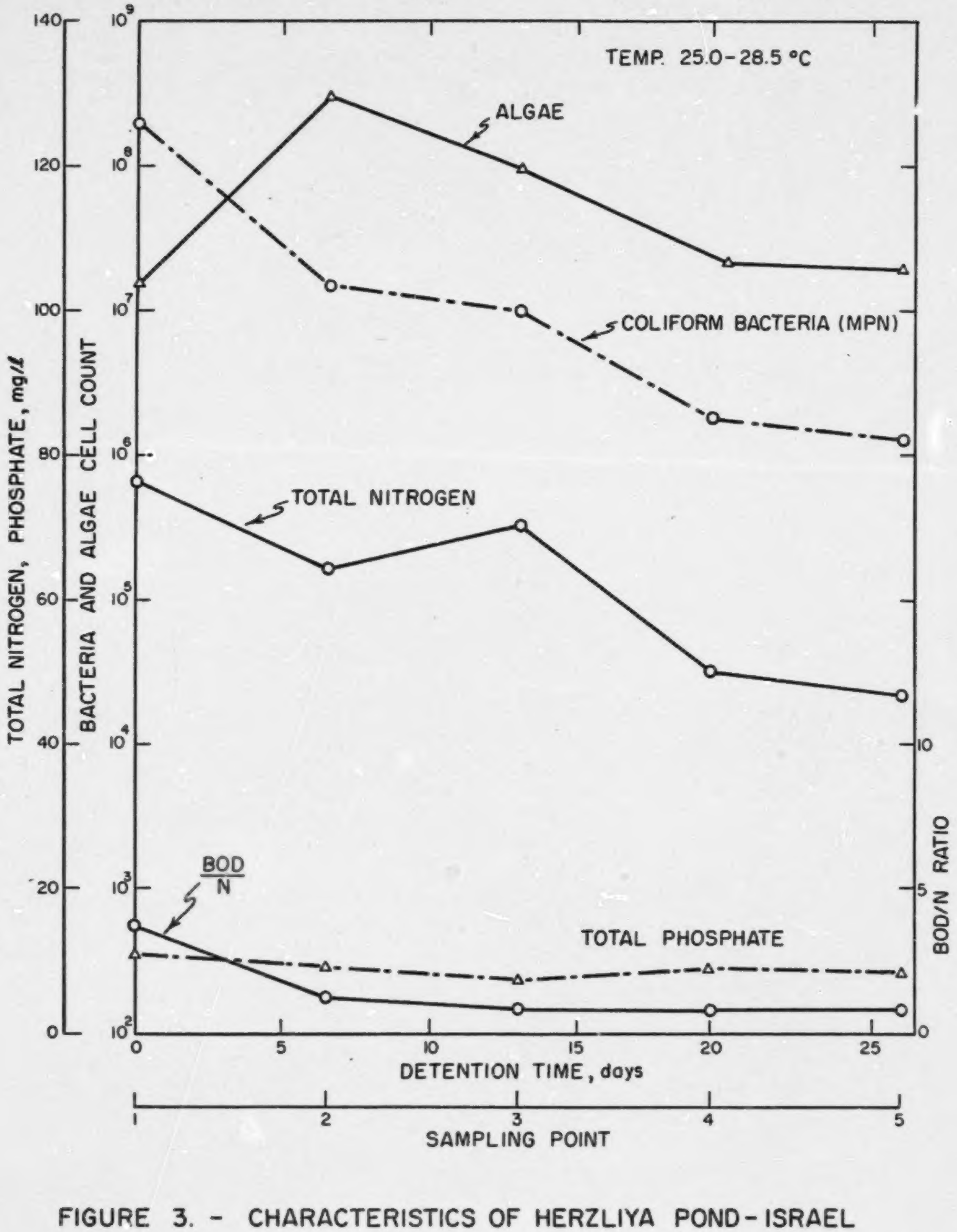

FIGURE 3. - CHARACTERISTICS OF HERZLIYA POND-ISRAEL

the BOD/P ratio was observed. Between sampling point 1 to 5 the ratio declined from 27.3 to 4.5.

The change of quality of the sewage as a function of detention time in the Herzliya stabilization pond system is plotted in Figure 3.

SUMMARY

Considerable data can be found in the literature on the function and performance of single facultative ponds, but relatively little data are available on the performance of complete stabilization pond systems in which various ponds perform different functions. In other words, little data on deep anaerobic and/or deep facultative ponds, high-rate ponds and polishing ponds are available. In addition, systematic evaluations of the position of stabilization ponds and/or stabilization pond systems in regard to other treatment units are hard to find.

Extensive literature exists on algae and algae growth in laboratories, natural waters, and stabilization ponds, but not all the data can be related to performance of stabilization pond systems. Less data are available on bacteria in stabilization ponds; while data on grazing organisms, which seem to play an important role in stabilization pond systems, are minimal.

Many papers have been published on the influence of temperature and light conditions on the growth of algae and general pond performance, but less data on gas production and gas exchange in stabilization ponds can be found in the literature. On eutrophication and related algae growth, much literature is available; but data on the nutritional needs of algae in highly eutrophic conditions such as those in stabilization ponds are scarce.

In other fields such as agriculture and composting which are subject to random and uncontrollable changes in light and temperature, there is a long history of nutritional research leading to the establishment of nutrient balances and nutrient ratios for their systems which improve yields in spite of changing environmental conditions. One would therefore assume that nutritional research for algal growth in waste ponds which are also subject to uncontrolled environment should yield benefits similar to those gained in agriculture and elsewhere.

A few investigations on sludge accumulation in single ponds receiving raw sewage have been made, but no data could be found on sludge accumulation or other "aging" factors for other pond units or complete pond systems.

None of the review papers on stabilization ponds and stabilization pond systems specified simple tests or analysis which could be carried out by plant operators and would be helpful in the day-to-day operation of stabilization ponds.

III. MATERIALS AND METHODS

SAMPLING AND THE TIME FACTOR IN SAMPLING

Sampling Methods

Raw sewage composite samples were collected over an 8 to 24 hour period and analyzed. For the pond liquids, however, only grab samples were collected and analyzed. Grab samples are justified when it is recognized that ponds, although subject to their own transcient variations, act as enormous integrators of influent waste and other factors, and, hence, time lapse composite sampling is unnecessary. Except for the two 24-hour runs involving the Richmond high-rate pond, and for analyses for dissolved oxygen which was conducted at the Saint Helena and Concord treatment plant laboratories, samples were collected in the morning hours and immediately transported to the Sanitary Engineering Research Laboratory (SERL) at the Richmond Field Station for analysis. When analytical techniques required it, e.g., determination of ammonia, fixation of the sample with sulfuric acid was done at the pond site. Upon arrival at the Richmond Field Station, the samples were stored in the refrigerator until the analyses were made. Ammonia and chlorophyl were analyzed within two hours, and all other determinations within one day. The 24-hour run samples at the Richmond Field Station were filtered and then stored in the refrigerator. The subsequent analyses of those samples took up to one week.

A special sampling device for depth samples was constructed. This sampling device was a long pipe with a flexible base for a test bottle. The stopper of the test bottle had two holes, through one hole the pond liquid could enter, and through the other the air could escape. A long rubber hose attached to the pipe was connected to the one hole through which the air could escape. For depth samples, the test bottle was lowered to the required depth with the air hose closed; after opening the air hose, the pond liquid entered the test bottle at the required depth.

Time Factor in Sampling

The designation "time factor in sampling" as used in this dissertation, refers to the effects on the experimental results coming from the timing followed in the sampling program, and from the insufficiency of the record of the environmental conditions which prevaled before sampling. Although environment is known to profoundly effect the performance of ponds, records of the major environmental factors, light and temperature were not made continuously because of the limited resources available for this study and, with the exception of Richmond, the remoteness of the study sites. Only grab samples--and these were gathered only once a week--were collected from the Concord and Saint Helena ponds while environmental conditions occurring several days prior to the sampling day were not observed or recorded adequately. The unrecorded environmental conditions which prevailed three or four days prior to the actual sampling day very likely had an as yet unknown effect on the pond characteristics on the day of the sampling. In future studies, such prior effects should be measured, recorded, and evaluated. However, the extremely limited resources available for the study herein reported made necessary a less exact procedure.

Apologetic!

ANALYTICAL METHODS

The analytical work described in this dissertation was performed on filtered samples in accordance with various methods specified herein.

The five-day biochemical oxygen demand (BOD), the chemical oxygen demand (COD), the dissolved oxygen (DO), total alkalinity, calcium, magnesium, and phosphate determinations were made according to procedures given in Standard Methods (52). For phosphate determinations, The ANS method of the Standard Methods was used.

Nitrate determinations were first made by the phenoldisulfuric acid method as described in Standard Methods (52), but because of limitation of accuracy by this method at low concentrations of nitrate (0.1 mg/l), the more sensitive Cadmium Column Method was used (120). Because the cadmium column method is a relatively new one, it is described in some detail herein.

The concentration of nitrates in water samples is determined in this procedure by first reducing the nitrates to nitrites and then colorimetrically determining the concentration of nitrites. The reduction is accomplished by passing the water sample through a cadmium-copper column. The nitrites which are thus formed are then treated with sulphanilamide and N (1-napthyl)-ethylene diamine dihydrochloride to form a diazo compound which is colored and obeys Beer's law at 543 mu.

Since some nitrites may be present in the sample prior to reduction, the concentration of nitrites originally present is determined by the addition of sulphanilamide and N-(1-napthyl)-ethylenediamine to a portion of the original sample and the color read at 543 mu. This concentration is subtracted from results obtained after the reduction.

Based on the total alkalinity determination, the three major forms of alkalinity, i.e., bicarbonate, carbonate and hydroxide, and carbonic acid were determined with the help of a newly developed computer method by Thomas and Trussell (87, 88). In this method the three above-mentioned forms of alkalinity are determined on the basis of the total alkalinity, the temperature and the pH levels (118). A copy of these computer determinations can be found in Table A-8 (Appendix A). It should be noted that the buffer capacity as defined in this program is the buffer capacity for changes in $CO_2(\frac{pH}{CO_2})$ but not for the changes in OH^-. Inorganic carbon for the August 20-21, 1969 run at the Richmond high-rate pond was calculated by using the similar, sounder method for alkalinity (89), i.e., the calculations were also based on total alkalinity, temperature and pH levels. After the August 20-21, 1969 run, carbon determinations were made by the carbon analyzer Model 915, manufactured by Beckman Instruments, Inc. (90). With this instrument, dissolved organic and dissolved inorganic carbon, organic and inorganic carbon of the solid fraction, as well as total carbon, (T-C) were analyzed. Although total carbon analyses were used generally because of budgetary limitations, only one complete fractional carbon analysis was made on the Concord and on the Saint Helena pond systems. Total carbon analysis for every one-hour sample at the October 21-22, 1969 sampling run at the Richmond high-rate pond was made.

The suspended solids in all pond liquids investigated and those of the secondary clarifier effluent in Concord could pass through the injection needle of the instrument having a diameter of 170μ. Consequently, all four carbon fractions (liquid dissolved organic and inorganic, solid organic, and inorganic) could be analyzed for sampling points 2, 3, 4, and 5 in Concord, and for sampling points 2, 3, 4, 5, and 6 in Saint Helena. Because of the inability to analyze larger solids with the Beckman instrument, only the total carbon of the raw sewage (sampling point 1 in all systems) has been analyzed.

Concentrations of total suspended solids and volatile suspended solids were determined in accordance with the SERL Analytical Methods (91). Nitrogen and ammonia were analyzed with the use of the AOAC micro-kjeldiehl method (92). Using this method the fixed ammonia sample was first adjusted to a pH of 7.2 with a phosphate buffer. Thereafter, the sample was distilled into a 10% boric acid solution and then titrated with a 0.0200 normal H_2SO_4. Methyl red and bromcresol green were used as indicators. As known, nitrite and nitrate are not detected by this test, but for the reason that only very small amounts of nitrate have been detected in the pond systems, the term total-nitrogen is used for the amounts detected by the above-mentioned micro-kjeldiehl method.

The biomass of algae was mainly determined as volatile solids by the SERL method mentioned above. However, the chlorophyll content also was used as an additional indicator for biomass and of the general condition of the algae. Chlorophylls a and b were determined according to the McKinney method (93).

The concentrations of all substances are reported in terms of concentration of the principal elements, with the exception of phosphorus which is reported in mg per liter as phosphate.

Algal counts and algal identifications were made with the Spencer hemacytometer counting chamber. The 100x magnification was used for gross counts, and the 430x magnification for identifications.

The BOD, COD, and T-C Test

Special attention was given to the BOD, COD, and T-C (total carbon) test in the studies described herein.

The BOD Test. Biochemical oxygen demand (BOD) usually is defined as the amount of oxygen required by living microorganisms (bacteria, protozoa and others) while stabilizing decomposable organic matter under aerobic conditions.

The term "decomposable" may be interpreted as applicable to carbohydrates and other easily oxidizable material.

A commonly used expression to calculate BOD is:

$$Y = L\,(1 - 10^{-Kt}) \qquad (3\text{-}1)$$

where,

Y = BOD at any time t,

L = the total or ultimate BOD

K = the rate constant to be determined.

The advantage of this expression is the possibility of determining the rate constant, K, under laboratory conditions which has been successfully translated to actual outdoor conditions in streams, lakes, and ponds.

The COD Test. The chemical oxygen demand (COD) test is based upon the fact that all organic compounds with a few exceptions can be oxidized to carbon dioxide and water by the action of strong oxidizing agents under acid conditions. For example, glucose and lignin are both oxidized completely. As a result of the completeness of oxidation, COD values are greater than BOD values and may be much greater when significant amounts of biologically resistant organic matter is present. In applying the COD test, however, some common biodegradable organic pollutants such as pyridine, benzene, and toluene are not oxidized, while certain inorganic compounds which do not affect the BOD analysis are oxidized.

The advantage of the COD test in comparison to the BOD test is the speed of the COD test, i.e., 2 hours instead of 5 days, and its application for industrial wastes with little biodegradable matter.

(T-C) Test. The carbon analyzer manufactured by Beckman Instruments, Inc., (Model 915), is a new tool with many applications in water pollution research. With this instrument, inorganic carbon, organic carbon, and total carbon can be measured (but not the required oxygen as measured in the BOD and COD tests). Measurements made with the carbon analyzer are independent of such factors as toxicity, biodegradability, chemical structure, or susceptibility to chemical oxidants. The above-mentioned factors are clearly big advantages particularly from an analytical standpoint. In addition, the test requires only 10 to 15 minutes to perform. Like the COD test, it tells nothing regarding the biological degradeability or availability of substances.

IV. STUDY RESULTS

STUDIES OF THE RICHMOND HIGH-RATE POND

Introduction

After several years of experimentation with small outdoor ponds under natural conditions of illumination and temperature, the basic design and operation criteria for high-rate ponds have been developed. These basic design and operation criteria are summarized as follows: 1) "The high-rate pond has to be shallow; lined; loaded heavily with organic wastes rich in nitrogen, carbon, and phosphorus; and provided with equipment with which the pond contents can be mixed at least once each day at a velocity of about 1 foot per second (94). These criteria were followed in designing and constructing the high-rate pond at the Richmond Field Station. For several years, experiments and research work have been conducted in which this pond was used to produce algae for studies on the nutritional characteristics of algae as a feedstuff for large farm animals (23). Following the conclusion of these studies, the pond has served as a source of algae for researchers in various parts of the world. To supply the researchers, the algae are harvested from the pond in required amounts and dried prior to shipment. As a result of experience gained over the years, it became apparent that certain problems in the operation of a high-rate pond as an algal growth unit and as a nutrient removal device would have to be solved before it could be introduced into conventional practice.

The present study undertook to answer some of these operational problems, namely those related to the high pH levels. At high pH levels microbial activity is reduced and nutrients are released or precipitate together with some microorganisms, and failure of the pond to produce algae consistently during summer months and those related to pond lining in terms of the inability to retain an adequate sludge layer uniformly distributed over the pond bottom.

Description of the High-Rate Pond

The Richmond high-rate pond is part of the Sanitary Engineering research Laboratory (SERL) sewage treatment facility which receives raw domestic sewage from a 24-inch diameter trunk sewer of the city of Richmond, California sewerage system. A pumping station, equipped with two alternating 75 gallons per minute pumps, delivers sewage through a force main to an elevated sedimentation tank. A distribution box splits the incoming flow, one portion flowing through a comminuter into a rectangular sedimentation tank, the remainder flowing to the high-rate pond. Through a by-pass arrangement, either, all or any desired fraction of the primary sewage can also be conveyed to the high-rate pond. The unused sewage flows back into the sewer system. A typical analysis of the pond influent is listed in Table VII.

The high-rate pond proper is 80 feet wide, 334 feet long, and occupies an area of 0.6 acre, and has a volume of 1 million liters at a 16-inch (40 cm) depth. As shown in Figure 4, three baffles divide the pond into four channels, each with an approximate width of 19.0 feet. At one end of the pond, a pump sump and 4 mixing pumps are located. These four mixing pumps deliver 1,750 gpm at a 12-inch head. When all four pumps are operated simultaneously, the liquid is moved at 1.0 feet per second from the pump discharge into the first channel. The pond bottom and the side slopes are lined with asphalt (1.25 inch asphalt based on 3.0 inches of crushed rock). The pumping facilities have a reinforced concrete base.

TABLE VII

Typical Analysis of the High-Rate Pond Influent

BOD	177.0 mg/l
Total Carbon as C	135.0 mg/l
Total Nitrogen as N	35.2 mg/l
Ammonia as N	26.0 mg/l
Phosphate as $PO_4^{\equiv}$	10.1 mg/l
Calcium as $CaCO_3$	148.8 mg/l
Magnesium as $CaCO_3$	66.7 mg/l
Alkalinity as $CaCO_3$	226.0 mg/l
pH	7.4

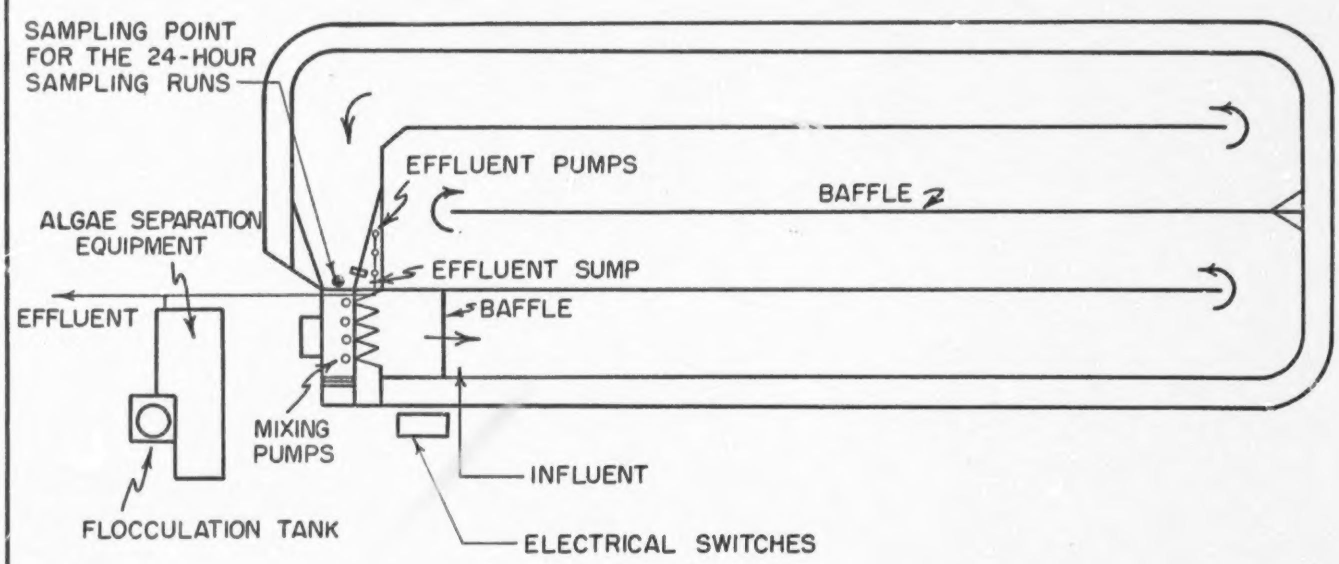
SAMPLING POINT
FOR THE 24-HOUR
SAMPLING RUNS
EFFLUENT PUMPS
BAFFLE
ALGAE SEPARATION
EQUIPMENT
EFFLUENT SUMP
EFFLUENT
BAFFLE
MIXING
PUMPS
INFLUENT
FLOCCULATION TANK
ELECTRICAL SWITCHES

FIGURE 4 - THE RICHMOND HIGH-RATE POND

Study Procedures

The study herein reported was started in late July 1969. At that time a pump breakdown resulted in a reduced pond loading and an increase in detention time of up to 20 days. The long detention times led to a sludge accumulation in the pond. At the same time an invasion of rotifers and ostracods occurred. It was decided, therefore, to drain the pond, to remove the sludge, and to apply $Ca(HOCl)_2$ for pond disinfection. During the drying period, sludge which had accumulated prior to that time was measured and observed. The results of the sludge study are given in a separate paragraph later in this section. Thereafter the pond was refilled and put into operation for several weeks. During this period a healthy algal population reestablished itself.

The first 24-hour sampling was started at 8 AM on August 20, at a time of optimal algal growth conditions, and was terminated at 8 AM the following morning, i.e., on August 21, 1969. The second 24-hour sampling program was started two months later during a period of lower temperatures, shorter daylight times, and less favorable algal growth conditions. The second 24-hour sampling program was begun at 8 AM on October 21 and concluded at 8 AM October 22.

Temperature and pH readings were taken hourly, at the time of collection of a one-gallon sample of the pond liquid. The samples taken at the indicated sampling point in Figure 4 were analyzed for alkalinity in its various forms--calcium, magnesium (total hardness), as well as nitrogen and phosphate.

The August 20-21, 1969 sampling run was to some degree an exploratory run. For example, carbon analysis which were found later in the research to be very important were not conducted in the August run although they were calculated later on the basis of total alkalinity, temperature, and pH by Saunders Method (89). No total nitrogen values were obtained in this run.

Study Results

General. In Tables VIII and IX are summarized the maximum, minimum, and mean values for temperature, pH, and all chemical constituents analyzed from samples taken in the two 24-hour sampling runs as given in Appendix A. The information in the two tables will enable the reader to discern the characteristics and trends described in greater detail in the following section.

The First 24-hour Sampling Run - August 20-21, 1969: Temperature Readings and pH Levels. In Table A-1 ("A" refers to Appendix A) is given the hourly pH levels and temperature readings. Figure 5 depicts these readings together with the readings recorded during the 24-hour sampling run in August 1969.

The average temperature of the pond liquid in the August sampling run was 21.4°C. The peak temperature occurred at 4 and 5 PM. It was 26.5°C. The minimum temperature of 17.5°C was recorded at 9 AM. The pH readings for this run indicate a peak of 11.05, and a minimum reading of 10.30 at 7 AM.

Considering that according to Oswald (37), the optimal pH values for algal growth and sewage oxidation are within the pH range of 7.0 to 8.5, and optimal temperatures are close to, but not higher than, 20°C, the pond failure which occurred on August 22 (one day after the sampling run) is understandable. Many of the chemical characteristics of the pond liquid described in the following sections appeared to be related to and are partly a result of the temperatures and pH values noted.

TABLE VIII

Analytical Results for the November 20-21, 1970 24-Hour Sampling Run

	Units	Max	Min	Mean
Temperature	°C	26.5	17.5	21.38
pH	--	11.05	10.30	10.79
Bicarbonate	mg/l as $CaCO_3$	15.20	0.00	2.27
Carbonate	mg/l as $CaCO_3$	85.56	51.16	70.70
Hydroxyde	mg/l as $CaCO_3$	24.89	0.00	13.60
Total Alkalinity	mg/l as $CaCO_3$	110.45	61.36	83.16
Inorganic Carbon	mg/l as C	9.69	4.29	6.61
Calcium	mg/l as $CaCO_3$	34.00	28.60	32.01
Magnesium	mg/l as $CaCO_3$	50.50	17.60	34.80
Total Hardness	mg/l as $CaCO_3$	88.50	51.00	67.10
Ammonia	mg/l as N	0.00	0.00	0.00
Phosphate	mg/l as $PO_4^{\equiv}$	3.18	1.97	2.40

TABLE XI

Analytical Results for the October 21-22, 1970
24-Hour Sampling Run

	Units	Max	Min	Mean
Temperature	°C	23.00	13.40	17.80
pH	--	9.95	8.08	9.29
Bicarbonate	mg/l as $CaCO_3$	166.00	46.90	114.99
Carbonate	mg/l as $CaCO_3$	99.8	0.00	39.49
Total Alkalinity	mg/l as $CaCO_3$	166.00	146.70	154.48
Total Carbon	mg/l	59.00	40.00	50.08
Calcium	mg/l as $CaCO_3$	79.50	44.90	56.50
Magnesium	mg/l as $CaCO_3$	34.90	18.10	28.17
Total Hardness	mg/l as $CaCO_3$	94.70	77.30	83.88
Ammonia	mg/l as N	7.20	3.70	4.59
Total Nitrogen	mg/l	8.40	4.50	6.60
Phosphate	mg/l as $PO_4^{\equiv}$	10.70	4.30	6.90

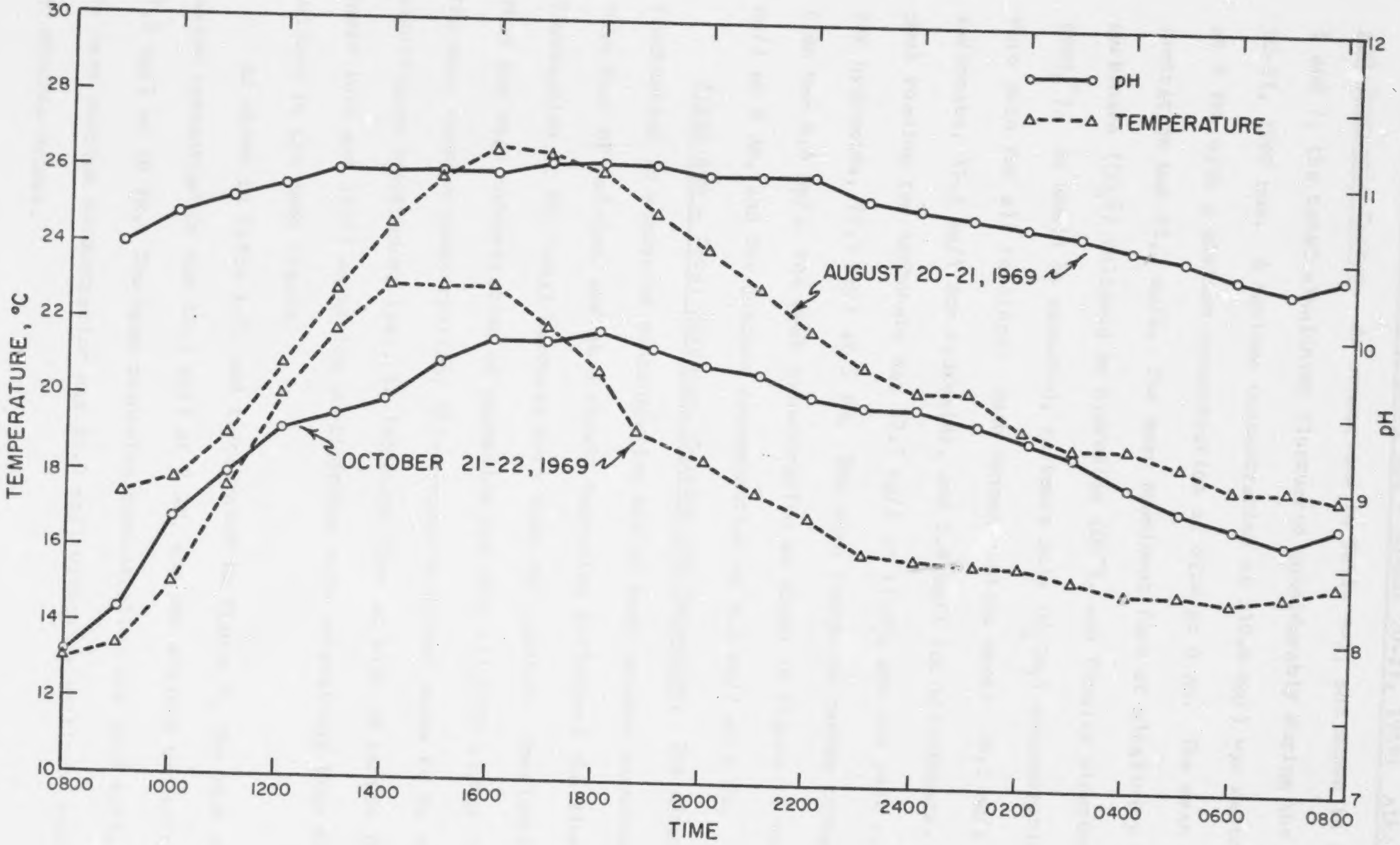

FIGURE 5 - DIURNAL SHIFT IN TEMPERATURE AND pH

The First 24-hour Sampling Run - August 20-21, 1969: Alkalinity and Inorganic Carbon. As summarized in Table A-3, and shown in Figures 6 and 7, the total alkalinity fluctuated considerably during the August 20-21, 1969 run. A maximum concentration of 110.4 mg/1 was recorded at 4 PM, with a minimum concentration of 61.4 at 4 AM. The mean concentration was 83.2 mg/1. The most prominent form of alkalinity was carbonate ($CO_3^=$) followed by hydroxide (OH^-), and finally bicarbonate (HCO_3^-). As would be expected, carbonic acid (H_2CO_3) concentrations were zero for all readings. Mean concentrations were: 39.1 mg/1 for carbonate, 37.3 mg/1 for hydroxide, and 6.8 mg/1 for bicarbonate. The peak reading for carbonate was 52.7 mg/1 at 11 AM, and the peak reading for hydroxide, 77.1 mg/1 at 5 PM. The mean inorganic carbon concentration was 6.6 mg/1, the peak concentration as shown in Figure 11 was 9.7 mg/1 at 8 AM, and the minimum concentration of 4.3 mg/1 at 4 PM.

First Run - Total Hardness, Calcium and Magnesium. The diurnal fluctuation in magnesium concentration was of much greater magnitude than that of calcium, and as a result magnesium influenced the diurnal fluctuation of the total hardness more than did calcium. Considering that the mean concentration of magnesium was only slightly higher than the mean calcium concentration, this magnesium effect seems to be of significant importance, i.e., it indicates that at high pH ranges (between 10.0 and 11.0) magnesium precipitates more extensively than does calcium in the pond liquid.

As shown in Table A-7, and illustrated in Figure 8, the peak magnesium concentration was 50.5 mg/1 at 7 AM, and the minimum concentration, 17.6 mg/1 at 10 PM. The mean magnesium concentration was 34.8 mg/1. The mean calcium concentration was 32.0 mg/1 without significant maximum and minimum values.

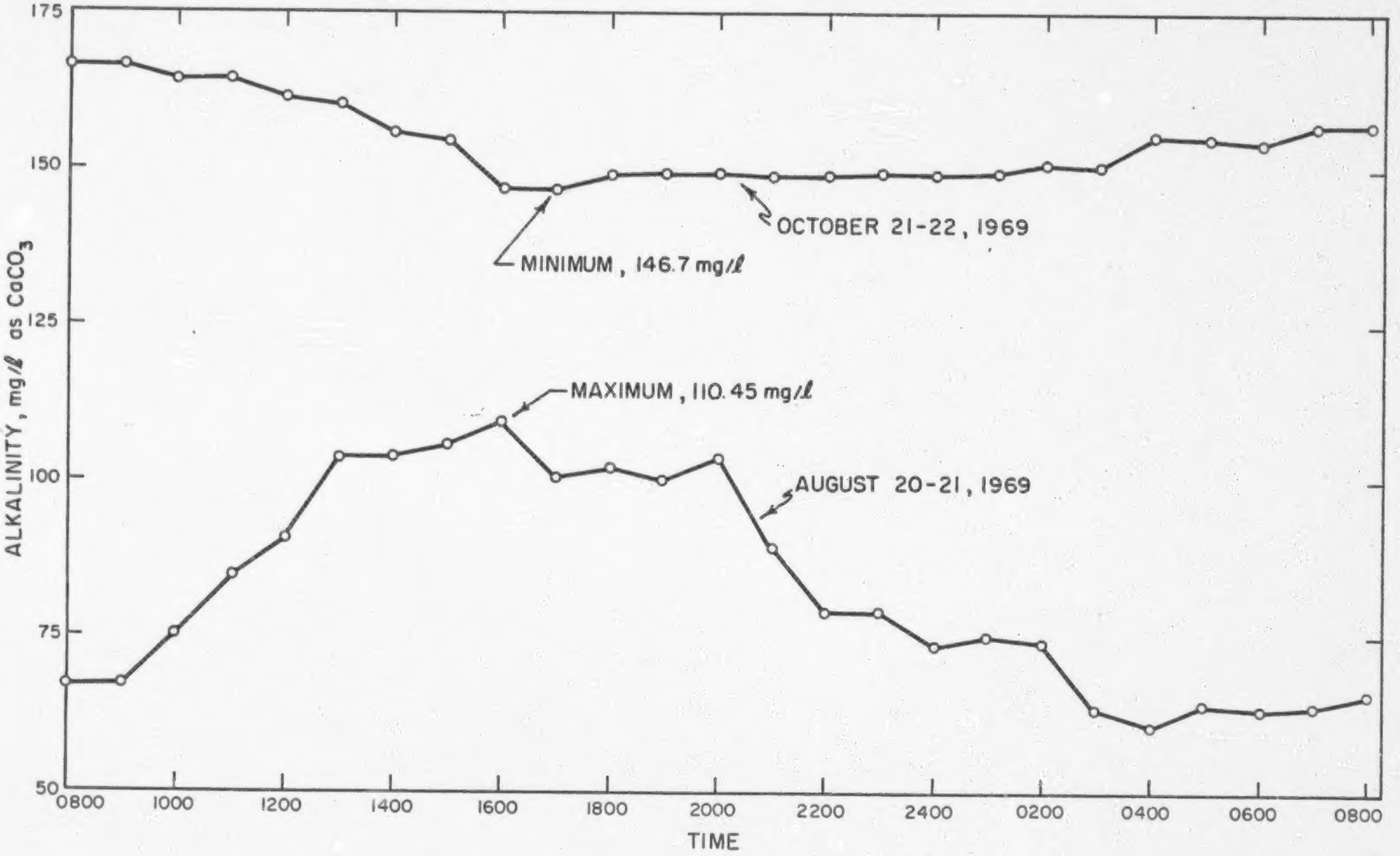

FIGURE 6 - DIURNAL SHIFT IN TOTAL ALKALINITY

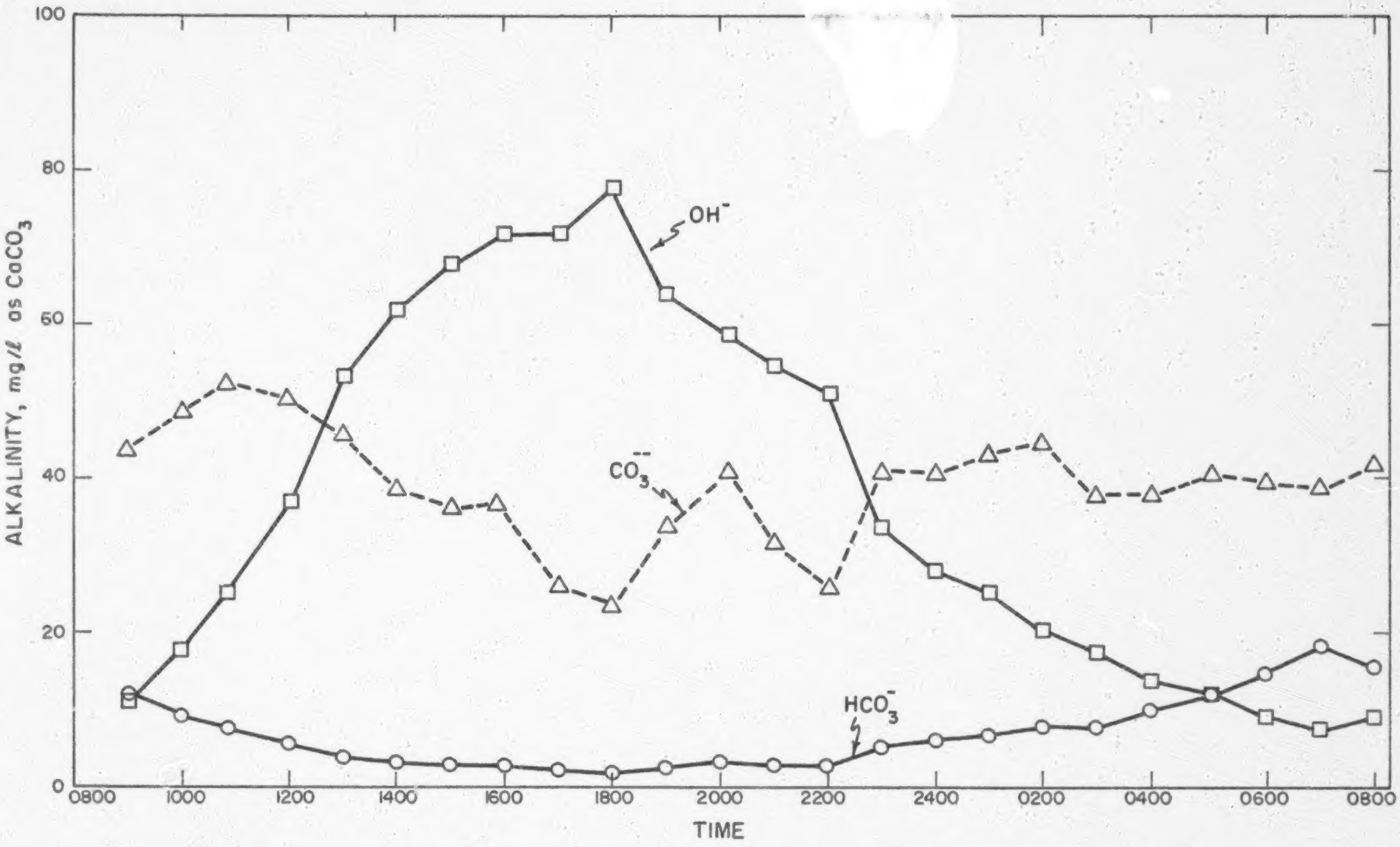

FIGURE 7. ALKALINITY COMPONENTS FOR THE AUGUST 20-21, 1969 SAMPLING RUN

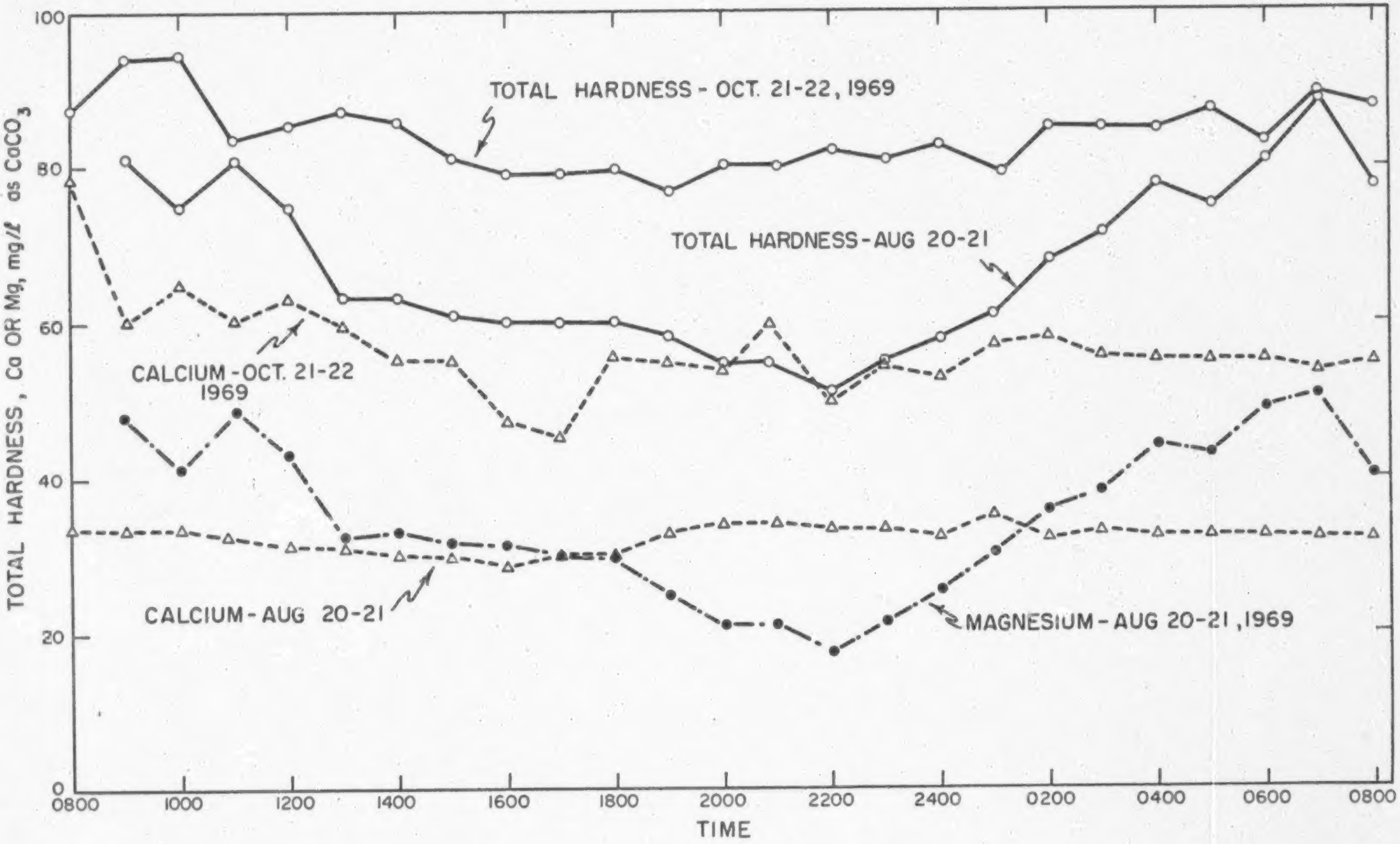

FIGURE 8.-DIURNAL SHIFT IN TOTAL HARDNESS, CALCIUM, AND MAGNESIUM

Phosphate and Ammonia - First Run. One of the most important findings of this 24-hour sampling run was the complete absence of ammonia. In addition to being assimilated by algae, indications are that ammonia was either released (driven off) into the atmosphere as a result of the high pH or dissipated in some obscure reaction. However, the zero findings for all the 24 hourly samples although unexpected are explained in the discussion (cf. page 230).

Phosphate concentrations as shown in Figure 9 were low and surprisingly stable (less precipitation than expected) with a mean value of 2.4 mg/1, a peak concentration of 3.2 mg/1 (9 AM), and a minimum concentration of 2.0 mg/1. All of these values indicate that in the high pH ranges, phosphate precipitation was less than expected. If available, 2.0 mg/1 of phosphate would support 68 mg/1 of algae.

Algae Counts and Algae Concentrations. In general, the greater part of the suspended solids contained in samples taken from the high-rate pond at Richmond between mixing periods is algal in nature, assuming, of course, that the sample is taken from the pond when the algal population is in good condition. The reason for the predominance of algal biomass is that the bacterial biomass generally is in a flocculent form and as such settles to the bottom along with other material of sewage origin directly after mixing ceases. This characteristic of pond cultures between mixing periods (i.e., during periods of quiescence was observed and reported by Oswald, *et al*. in 1958) (37).

At a period comparable to that of the August 20-21, 1969 sampling run, algal concentrations (as volatile solids) were determined and algal counts were made on September 8, 1970. In this September sample the algal concentration was 45.9 mg/1. The algal count was 1.02×10^5, and the predominant algal genus was *Ankistrodesmus*.

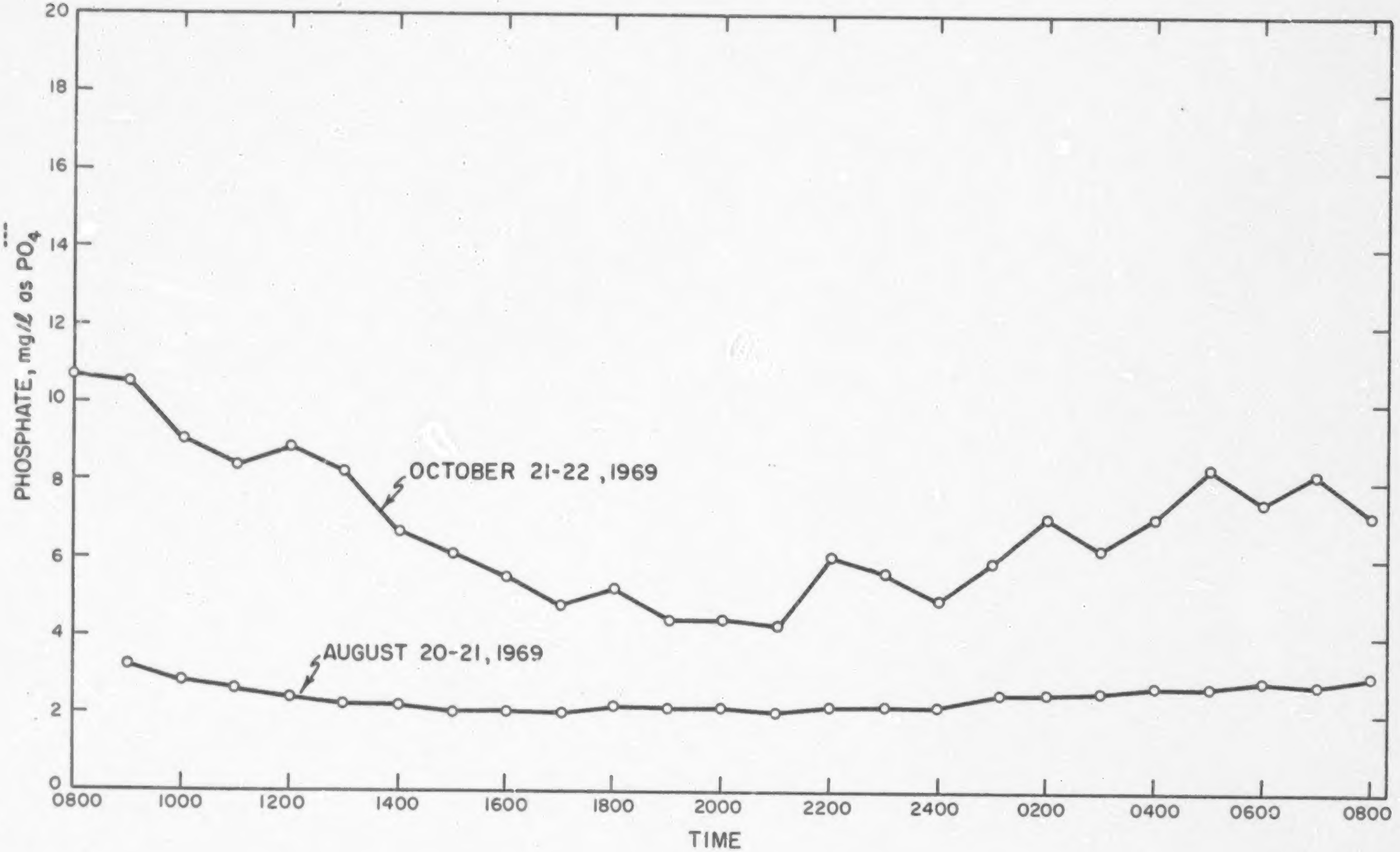

FIGURE 9.- DIURNAL SHIFT IN PHOSPHATE AS PO_4

The Second 24-hour Sampling Run - October 21-22, 1969: Temperature Readings and pH Levels. As expected, temperature readings and pH levels for the October sampling run were lower than those recorded for the August sampling run. These differences are clearly illustrated in Figure 5 where the data for both runs have been plotted. The mean temperature of the October run was 17.8°C, and the maximum temperature, 23.0°C. pH levels did not reach 10.0 and the maximum pH recorded was 9.95. The mean pH readings of 9.29 were still high, the minimum pH was also relatively high and never fell below a level of 8.00. Table A-4 summarizes all of the data on temperature and pH recorded during the October sampling run.

Alkalinity - Second Run. Because of the lower pH levels in this run, the alkalinity components were mainly bicarbonate and carbonate. Total alkalinity was stable when compared to the August alkalinity. The midday rise of hydroxide concentrations for the August run has been replaced by a carbonate rise in this run. This shift from hydroxide in the August run to carbonate in the October run can be seen in Figure 7 and Figure 10. As shown in Table A-5, the mean concentrations were 154.3 mg/l for total alkalinity, 119.0 mg/l for bicarbonate, 33.7 mg/l for carbonate, 1.3 mg/l for hydroxide, and 0.3 mg/l for carbonic acid.

Total Hardness, Calcium and Magnesium - Second Run. The total hardness concentrations in the October sampling run were substantially higher than in the August sampling run; and, in addition, were relatively stable during the whole 24-hour period. The mean concentration for calcium was 56.5 mg/l; for magnesium, 28.2 mg/l; and for total hardness, 83.9 mg/l. By comparing these mean concentrations with those recorded for the August run, a shift from magnesium prominence to calcium prominence

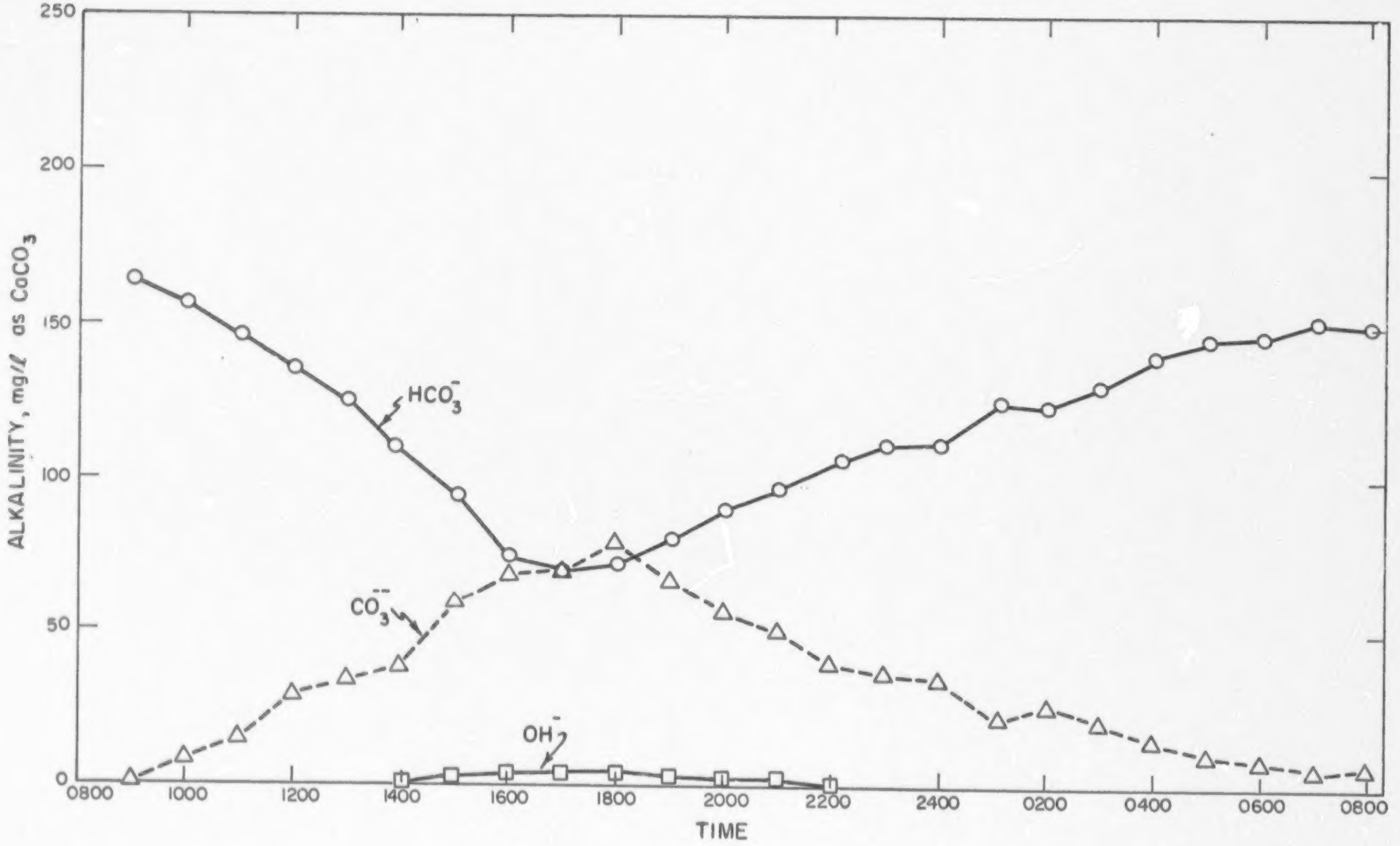

FIGURE 10. ALKALINITY COMPONENTS FOR THE OCTOBER 21-22, 1969 SAMPLING RUN

can be observed. The higher calcium concentrations in this sampling run indicates that in time when pH rises, calcium precipitates first and magnesium thereafter. The complete data for the total hardness and its two components are summarized in Table A-6 and are illustrated in Figure 8.

Carbon, Nitrogen and Phosphate - Second Run. The mean concentrations for total carbon, total nitrogen, and phosphate are given in Table X and all additional data are given in Tables A-7, Figures 9, 11, and 12. In order to make it possible to compare the summarized concentrations as given in Table X with those in the raw sewage, the nutrient concentrations for the raw sewage, as well as the reduction of these nutrients due to the treatment, have been added to this table.

The reductions in nutrient indicated in Table X give important information in regard to the change in the nutrient balance between the raw sewage and the liquid in the high-rate pond. The reduction of 81.3% of nitrogen, compared with a lower reduction of 62.8% of carbon, and a still lower reduction of only 31.7% of phosphate should be particularly noted.

It should be remembered that no pond failure occurred after this October sampling run and that temperature and pH levels were not as high as in the August sampling run.

Assuming an average C/N/P ratio of 100/12/2.5 for normal average uptake through algae, a reduction of 84.9 mg/l of carbon should cause a reduction of 10.6 mg/l of nitrogen and 2.1 mg/l of phosphate. As indicated above, phosphate removal was within expected limits, and a reduction of 3.2 mg/l indicates that the carbon to phosphate uptake ratio was 100 to 3.75. This ratio is well within the normal biological range of uptake.

TABLE X

Nutrient Concentrations and Nutrient Ratios

	C mg/1	N mg/1	P mg/1	C/N	C/P	N/P
Raw Sewage	135.0	35.2	10.1	3.83	13.38	3.38
Pond Liquid	50.1	6.6	6.9	7.57	7.23	0.96
Reduction mg/1	84.9	28.6	3.2			
Reduction %	62.8	81.3	31.7			

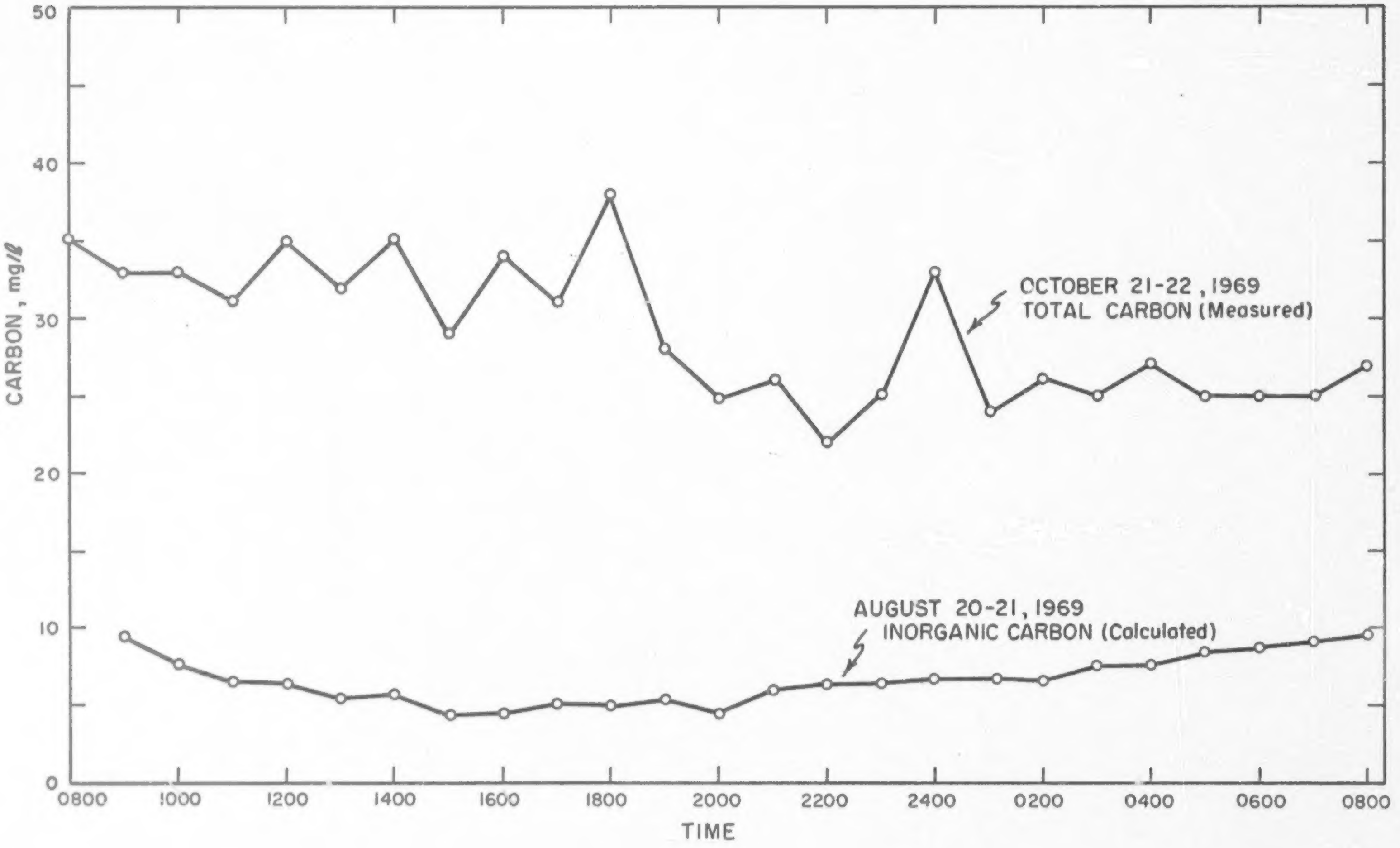

FIGURE 11. - DIURNAL SHIFT IN CARBON

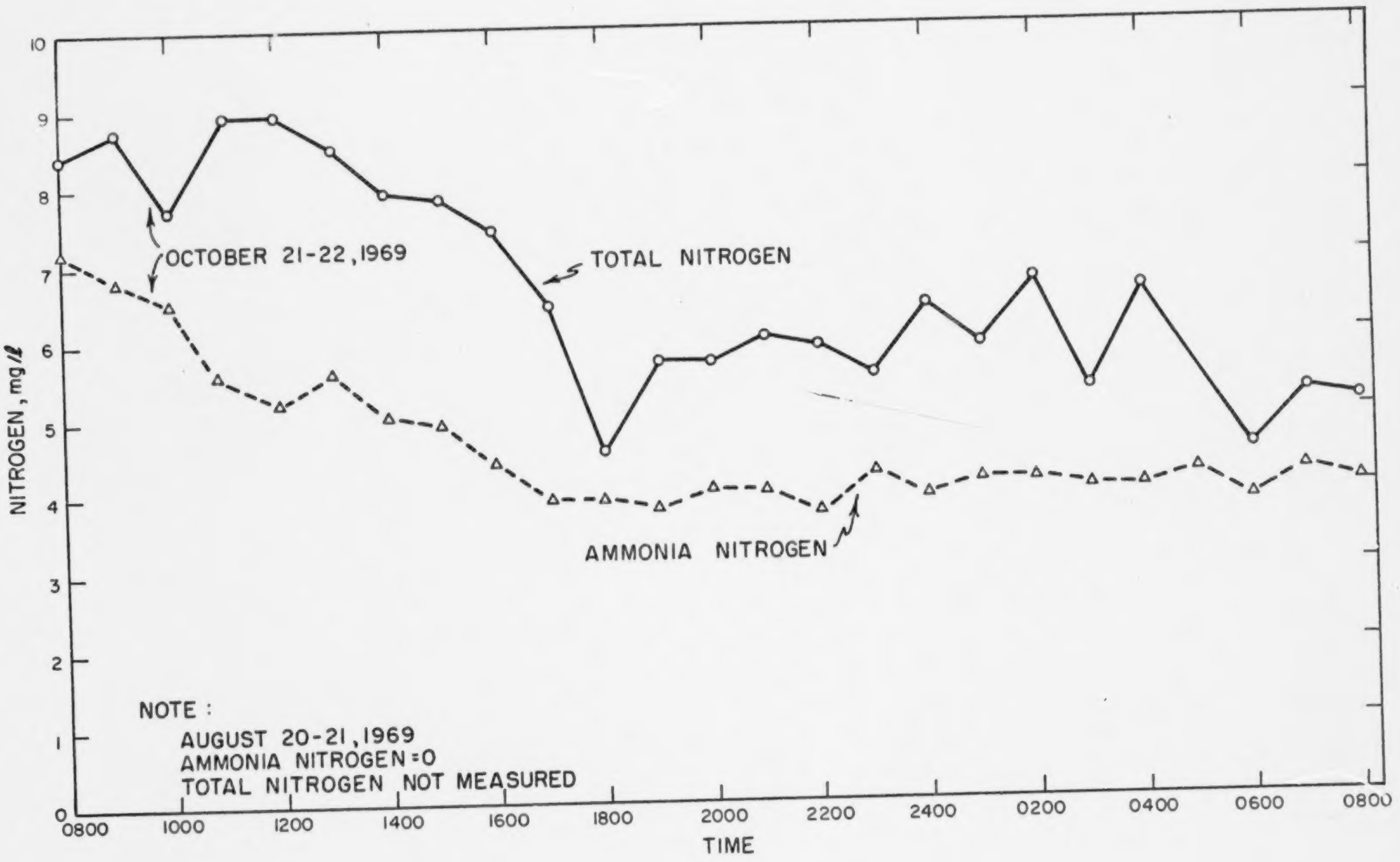

FIGURE 12 - DIURNAL SHIFT IN TOTAL NITROGEN AND AMMONIA

Because pH levels in this run were always below 10.0 (see Figure 5), it seems that only a portion of the phosphate precipitated.

The nitrogen removal picture is different, however. The reduction of nitrogen was 28.6 mg/l corresponding to a ratio of 100 to 33.8. This ratio is above the normal range of uptake to be expected on the basis of algal composition and/or a nutrient uptake of about 18 units of nitrogen for 100 units of carbon (see Table V). These findings correlate well with Golueke's et al. findings (96) which also indicate ammonia losses in the Richmond high-rate ponds.

The big differences in the percentage of nitrogen and phosphate reduction brings a new element into the nutrient balance picture. This new element indicates that there not only is an imbalance in the raw sewage which influences the nutrient uptake by algae, but that a shift in the nutrient balance occurs as the sewage proceeds through the different treatment stages. In the Richmond high-rate pond, this shift is toward carbon deficiency in regard to phosphate but not in regard to nitrogen. This is an additional indication that the complete removal of phosphate (from domestic sewage origin) through the uptake of algae in stabilization ponds is only a remote possibility unless algal removal is also practiced.

Analysis of a Pond Failure

In previous studies and pilot plant experiments, breakdowns of algal cultures in outdoor ponds have been observed. In this study a high-rate pond failure occurred one day after the August sampling run. Long daylight hours caused the high-rate pond to act as a heat sink, as was indicated by relatively high temperatures persisting after sunset. This phenomenon has also been observed in previous studies (23). High pH levels prevailed throughout the 24-hour period with a maximum of 11.05 and a minimum of 10.30.

Data collected on the August 20-21 sampling run immediately preceding the pond failure may be compared to those for conditions of the October 21-22 sampling run (a sampling run with shorter daylight hours, lower temperatures, and lower pH levels), in order that the causes of pond failure may be explored. It should be understood that the following narrative analysis of pond failure is only a hypothesis and changes in the hypothesis may have to be made as more data become available.

The inorganic constituents of sewage and pond liquids are essentially the same as those present in natural waters, and their buffer capacities are dominated by the carbon dioxide-bicarbonate-carbonate buffer system (97, 118). The phosphate and ammonia buffer systems are generally less predominant. This was the case in the Richmond high-rate pond, where the influent concentrations were approximately 226 mg/l as $CaCO_3$ for alkalinity, 26.0 mg/l as N for ammonia, and 10.1 mg/l as $PO_4^{\equiv}$ for phosphate. The carbon dioxide-bicarbonate buffer system has two pKa values--one of 6.35 and one of 10.33 at 25°C (98). Since the pH values in both runs were always higher than 8.0, we are concerned with the buffer system around the pKa_2 value of 10.33 (25°C). It is well known that the bicarbonate-carbonate system has ample buffer capacity in the 9.5-11.0 pH range, but little capacity (approximately 20% toward the alkaline side) is left when the pH level of 11.0 is reached. Considering the fact that the carbonate buffer system is the most important of the three systems, only this buffer system will be considered in the following descriptions. This carbonate system is commonly measured as alkalinity and the previously mentioned analysis for the high-rate pond influent indicates a mean alkalinity of 226 mg/l. The progress toward pond failure is outlined in the following 12 points.

1. Since bicarbonate is the major component in the neutral and low alkaline range, bicarbonate is used as the starting point. From this starting point, the hydroxide formation may be shown as:

$$\begin{array}{l} \mathrm{Na\,H\,CO_3} \rightleftharpoons \mathrm{Na^+ + HCO_3^-} \\ \mathrm{H\,CO_3^- + H^+} \rightleftharpoons \mathrm{CO_2 + H_2O} \\ \mathrm{H\,O\,H} \rightleftharpoons \mathrm{H^+ + OH^-} \\ \hline \mathrm{Na\,H\,CO_3} \rightleftharpoons \mathrm{Na^+ + CO_2 + OH^-} \end{array}$$

   Uptake of CO_2 by algae causes a shift to the right in this reaction and with the consequent production of OH^-.

2. However, if bacteria (in bottom sludge and in pond liquid) produce sufficient CO2 over a 24-hour period, the above equation can be kept in equilibrium

$$\text{Daytime:}\quad \mathrm{NaHCO_3} \longrightarrow \mathrm{Na^+} + \underset{\substack{\downarrow \\ \text{used by algae} \\ \text{photosynthesis}}}{\mathrm{CO_2}} + \mathrm{OH^-} \tag{1b}$$

$$\text{Night time:}\quad \mathrm{Na^+} + \underset{\substack{\nearrow \qquad \nwarrow \\ \text{CO}_2\text{ from bacterial} \qquad \text{Diffusion of} \\ \text{degradation} \qquad \text{atmospheric CO}_2}}{\mathrm{CO_2}} + \mathrm{OH^-} \longrightarrow \mathrm{NaHCO_3}$$

It is also likely that fermentation leads to formation of acid end-products, and that these acid end-products help to neutralize OH^-.

McLaren (99) indicated that water-saturated soil particles larger than about 3 mm in radius are anaerobic at their centers, and since particles of this size are present in most soils, microsites having anaerobic conditions may exist on the soil surface. By applying this type of reasoning to the sludge particles and/or small sludge pockets in the high-rate pond, the existence of anaerobic pockets within the aerobic pond seems to be probable; and hence the production of acid end-products (R-COOH) in addition to CO_2 probably occurs.

Parker (116) made extensive studies on sludge accumulation, gas yield, and gas composition at the Melbourne stabilization pond systems. A typical example of the sludge composition, gas yield, and gas composition that he observed is as follows: sludge composition, 4.2% total solids, 48.6% volatile solids (of total); gas yield, 5.8 ml/day/gram volatile solids; gas composition, CO_2 - 12.1%, O_2 - 0.2%, H_2 - 27.0%, CH_4 - 37.7%, residue - 23.0%.

Holmes and Vennes (109) investigated a stabilization pond at Grafton, North Dakota with a BOD load of approximately 260 lb/acre/day and measured the following amounts of acid end-products: formate from 10.9 to 270.6 mg/l; acetate from 0.0 to 772.0 mg/l; propionate from 0.0 to 13.1 mg/l; and butyrate from 0.0 to 63.7 mg/l. Longer chain organic acids have only been found in trace amounts or not at all. Thus, organic acid production in ponds is well documented.

3. On warm summer days with long daylight hours, the CO_2 uptake by algae during the daytime hours is greater than the CO_2 and organic acid production by bacteria during the day and night. The production of CO_2 and organic acids (including some products from the respiration of algae) during the short summer nights is not sufficient to cover the losses during the long summer days.
4. As a result of these losses, a reduction in carbonate alkalinity occurs.

$$NaHCO_3 \rightleftharpoons Na + \overset{\uparrow}{CO_2} + OH^- \quad \text{alkalinity decreases}$$

$$HCO_3 + OH^- \rightleftharpoons CO_3^{=} + H_2O \quad \text{alkalinity shift}$$

5. The pH levels begin to reach levels where bacteriostasis apparently occurs, and an already insufficient bacterial production of CO_2 + R-COOH is further decreased.

6. At this point algae are still growing rapidly and CO_2 uptake is accelerating. However, because of the low CO_2 production, there is almost no counter balance to the CO_2 uptake, therefore, pH rises even faster.

7. At these elevated pH levels, for example, in the range of 8.5 to 10.0, and as a result of mixing, ammonia is released to the atmosphere (See Figure 13) and calcium salts begin to precipitate;

$$NH_4^+ + OH^- \rightleftharpoons NH_4OH = \overset{\text{Released to atmosphere}}{\overset{\uparrow}{NH_3}} + H_2O \qquad (2)$$

$$2HCO_3^- \rightleftharpoons \underset{\downarrow}{CO_3^-} + H_2O + \overset{\text{Uptake by algae}}{\overset{\uparrow}{CO_2}} \qquad (3)$$

$$+ Ca^{++} \longrightarrow CaCO_3 \text{ precipitate}$$

Ammonia losses in the range of 15 to 31% were indicated by Golueke in a study at the Richmond high-rate ponds (96). These losses could not be accounted for other than by volatilization of ammonia and its loss to the atmosphere.

Other important salts (in addition to $CaCO_3$) which also may be precipitated at this stage are $Ca_3(PO_4)_2$ and $CaSO_4$. As soon as salts begin to be precipitated, it is possible that micronutrients and microorganisms may also be removed through adsorption.

8. After additional reduction of alkalinity, the pKa_2 level of 10.33 is

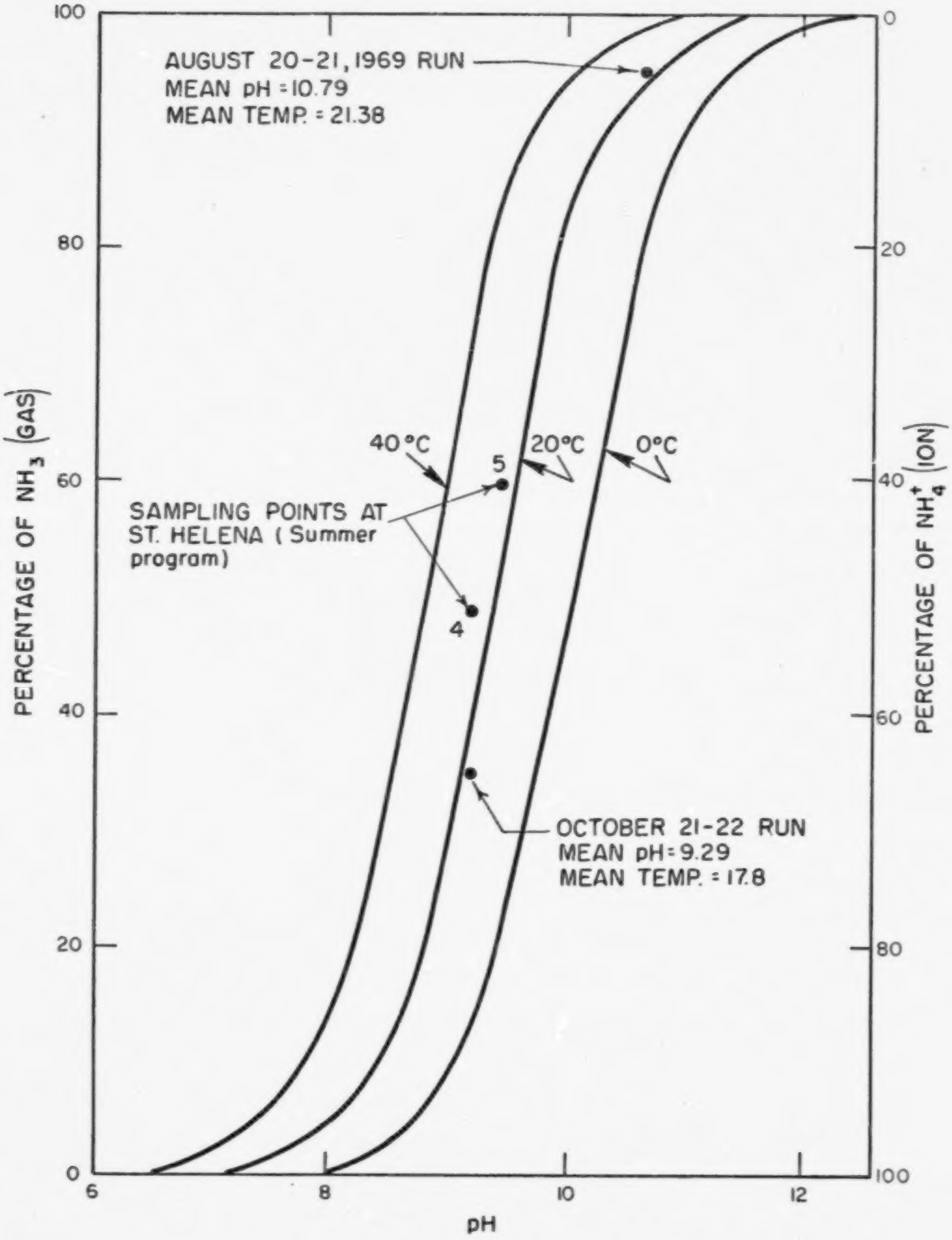

FIGURE 13 - EFFECT OF pH AND TEMPERATURE ON THE DISTRIBUTION OF AMMONIA AND AMMONIUM ION IN WATER (From Reference 100)

reached. From this point to the point where no bicarbonate/carbonate buffer is left (at an approximate pH of 12.0) the reserve of buffer capacity toward the alkaline site is increasingly depleted. For example, at a pH of 10.5, we have 78% of the alkalinity available as bicarbonate-carbonate, but at a pH of 11.0, only 20% is left.

9. At this high pH level (10.5 and higher), $Mg(OH)_2$ begins to precipitate. The floc of this precipitate adsorbs more micronutrients, and thus micronutrients precipitate together with the $Mg(OH)_2$ floc.
10. The remaining nutrients at this stage are quickly released to the atmosphere (ammonia) or precipitate out. Elevated temperatures (26.5°C during the period of the August sampling run) are an additional factor in accelerating reaction rates and subsequent precipitation.
11. The breaking point has now been reached, and algae begin to settle out and ultimately die. At these high pH levels and with high temperatures (see Figure 5), almost all biological activity ceases and the final breakdown of the pond takes place.
12. Nutrients then begin to accumulate, undergo acid decomposition and the cycle 1 to 12 is repeated.

The dearth of sewage to replenish nutrients has also been suggested as a major problem in the continuous operation of the Richmond high-rate pond. This is no doubt a problem, but inasmuch as the volume of sewage flow was comparable in both runs, and sewage strength was relatively constant throughout the experimental period, the supply of available nutrients also must have been comparable. Therefore, the pond failure which occurred directly after the August 20-21 run must have been due to many factors other than simple inadequacy of incoming nutrients.

Sludge Accumulation

As previously indicated, because of a pump breakdown at the end of July, 1969, it was decided to drain the pond and to remove the sludge. In time, with the pond empty, a sludge sampling program was carried out.

In this sludge sampling program, three samples were collected from the sludge during the cleaning operation, and nine samples were taken at different locations from the pond bottom when the pond was already dry. These nine locations are well spread over the surface and are representative of the overall sludge composition of the Richmond high-rate pond. Results of this examination are presented in Table XI.

As seen from Table XI,there were great differences between the sludge compositions of the collected samples. Sample 5, for example, taken from a point close to the influent, had 3.5% volatile solids and 96.5% fixed solids (sand, silt, etc.). Samples 1 and 2, on the other hand, were taken at sites close to the effluent of the high-rate pond. Their composition was typical of that of algal sludge. This algal sludge had 98.1 and 40.6% volatile solids. The mean percentage of volatile solids of all the 12 samples was 42.7%, leaving 57.3% for fixed solids.

For comparison, two samples from the pond influent were collected. They had 69.5% (mean value) of volatile solids. The solids represented by the difference between the two volatile solid fractions (69.5% - 42.7%) = 26.8%. This 26.8% left the pond mainly as algal cells.

Visual inspection indicated that the sludge from the lined pond was loose and without visible slime or other binding material of microbial origin. Microscopic observations indicated that algal cells were much more numerous than bacterial cells and that the bacterial population was substantially smaller than that observed in sludge samples from unlined ponds in Concord and Saint Helena.

From this small sampling program, as presented in Table XI,it can

TABLE XI

Sludge Composition of the Lined
Richmond High-Rate Pond

Sample Number	Volatile Suspended Solids %	Fixed Suspended Solids %
1	98.1	1.9
2	40.6	59.4
3	40.8	59.2
4	21.7	78.3
5	3.5	96.5
6	40.0	60.0
7	47.0	53.0
8	37.0	63.0
9	72.0	28.0
10	47.0	53.0
11	37.0	63.0
12	28.0	72.0
Mean	42.7	57.3
Standard Deviation	23.8	23.8
Coeff. of Variation	56%	42%

be seen that there are three different kinds of materials which accumulate as sludge:

1. Inorganic solids including sand, silt, and clay particles.
2. Volatile (organic) solids from sewage origin which settle out but have not been completely decomposed by bacteria.
3. Older algae which settle to the bottom and are subject to storage or decay.

Considering the high percentage of inorganic matter (57.3%) found in the Richmond high-rate pond, the inorganic solid accumulation would suffice for recommending that sludge removal devices or procedures be incorporated into lined high-rate pond design and into lined high-rate pond operation.

Conclusions from the Richmond Pond Study

If maximum utilization in outdoor high-rate ponds is the goal for efficient algal production, then all other growth factors except temperature should be at optimal conditions. However, as seen from the pond failure analysis, pH control is essential for an efficient high-rate pond operation. Therefore, pH is the first growth factor which must be controlled; and secondly, a sufficient and balanced nutrient supply must be maintained.

Although as previously mentioned, carbon is limiting in raw sewage, a shift to nitrogen deficiency appeared in this lined high-rate pond because of high pH, ammonia release and resulting CO_2 absorption. However, if we assumed that pH control will be applied, such a shift would not occur, and carbon would remain the limiting nutrient. If CO_2 were applied to achieve pH control, the CO_2 would also be utilized as a nutrient and thereby would bring about a more favorable nutrient balance for algal growth.

Two operational procedures, namely depth control and mixing, might also be helpful in preventing pond failure caused by accelerated algal growth with related high pH values. With regard to depth control, the operational depth of the pond should be adjusted to compensate for higher light intensities in summer and lower intensities in winter. Thus, it seems likely that the pond should be operated at shallower depths (approximately 8 inches) in winter, and at a greater depth (approximately 12 inches) in summer. As for mixing, during the two 24-hour runs the pond was mixed continuously for two hours at night. Daytime mixing would have the following advantages in summer: 1) induced turbidity would help prevent accelerated algal growth to the point of high pH; 2) oxygen (in over saturation because of high algal activity) could escape the pond, and CO_2 could enter the pond liquid. The mixing activities should be correlated with effective pH control, otherwise too much ammonia would escape the high-rate pond and excessive turbiduty would interfere with photosynthesis.

Phase isolation (101) (i.e., a separate bacterial unit and a separate algal unit) in series should also be considered as a possible solution to the failure sequence. Such a system would probably supply nutrients in greater amounts and in a much better balance. However, because of slow CO_2 delivery from the bacterial units, pH could still rise to undesirable high levels in the separate algal unit. Further experimentation is needed to indicate to which degree a bacterial unit would be able to supply CO_2 and R-COOH for pH control. A question arises, then: If phase isolation were used, would the 24-hour supply of CO_2 and R-COOH from the bacterial unit be able to compensate for the amounts used by high-rate algal growth during the daylight hours? This question and others will have to be answered in future experiments.

STUDIES OF THE CONCORD STABILIZATION POND SYSTEM

Introduction

The purpose of this study was to evaluate performance data on an existing stabilization pond system situated in the city of Concord, California.

The unlined high-rate pond of this system (the first municipal unit ever constructed) is mixed by recycling the entire pond volume through use of four lowlift, high-volume pumps. This mixing is sufficient to keep the entire depth of the pond aerobic. Under such conditions the unlined high-rate pond of the pond system has worked satisfactorily for about six years and which has consistently produced an effluent which has met the Regional Water Quality Control Board standards.

During the course of the study different performance aspects (algal growth, nutrient removal, carbon and BOD reduction) were investigated. Special attention and emphasis was given to the following problems: 1) the overall performance of the pond system with regard to treatment and nutrient removal; 2) the performance of each pond unit by itself; 3) nutrient requirements and nutrient balance for algal growth in the pond system; 4) the protective sludge layer at the bottom of the high-rate pond.

The Treatment Plant

The treatment plant of the city of Concord consists of:

1. A headwork - including pump stations, comminuters, and other equipment.
2. Sedimentation tanks - for primary treatment.
3. A two-stage trickling filter system with a secondary clarifier.
4. A pond system - consisting of three units--two anaerobic ponds in

parallel with an unlined high-rate pond and a partially lined high-rate polishing pond.

5. Post chlorination.
6. Discharge to Walnut Creek.

The average daily total sewage flow (from October 1968 to October 1969) was approximately 6.0 MGD (million gallons per day). An average flow of 1.4 MGD of raw sewage is pumped to the Central Contra Costa County Sanitation District (CCCCSD) treatment plant, and the remaining portion of 4.6 MGD is treated in the above-described Concord treatment plant. Because a portion of the sewage is treated at the CCCCSD treatment plant, the hydraulic and organic load at the Concord treatment plant is relatively constant.

Typical characteristics of the incoming raw sewage at the overflow structure (composite sample) are as follows: BOD - 178.0 mg/l; COD - 344.0 mg/l; T-C - 160.0 mg/l; total nitrogen - 30.9 mg/l; phosphate - 10.1 mg/l; and alkalinity - 221.0 mg/l.

The path of flow through the pond system is shown in Figure 14, and as noted on the figure, encircled numbers indicate sampling station location in the system. The final effluent is chlorinated and discharged into Walnut Creek. The creek occasionally is dry during the fall of the year, but carries heavy storm flows in winter, and has a dry weather mean flow of about 8 cfs. The quantity of diluting water in the creek is thus about equal to the quantity of waste discharged during most of the year. The required quality standards for the effluent discharge into the creek (as receiving waters) as set by the Bay Regional Water Quality Control Board are as follows: effluent: BOD - 20 mg/l; pH - 6.5-8.5; MPN - 1000/100 ml; receiving water: DO - 5.0 mg/l.

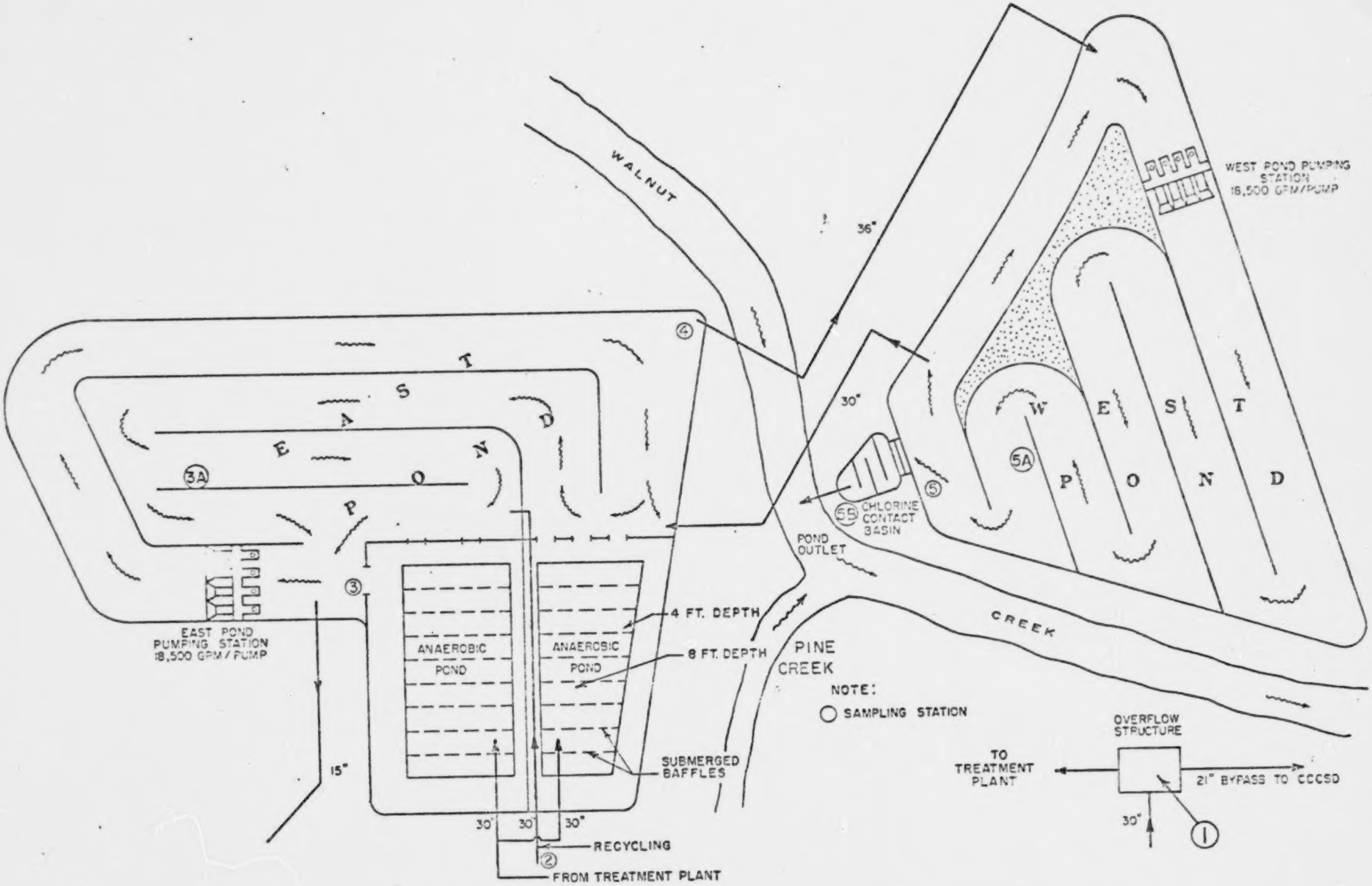
WALNUT
CREEK
PINE
CREEK
EAST POND
WEST POND
36"
30"
30"
30"
30"
15"
④
③
③A
②
⑤
⑤A
55
CHLORINE CONTACT BASIN
POND OUTLET
WEST POND PUMPING STATION 18,500 GPM/PUMP
EAST POND PUMPING STATION 18,500 GPM/PUMP
ANAEROBIC POND
ANAEROBIC POND
4 FT. DEPTH
8 FT. DEPTH
SUBMERGED BAFFLES
RECYCLING
FROM TREATMENT PLANT
NOTE:
○ SAMPLING STATION
OVERFLOW STRUCTURE
TO TREATMENT PLANT
21" BYPASS TO CCCSD
30"
①

FIGURE 14 - CONCORD STABILIZATION POND SYSTEM

The Stabilization Pond System

The pond system as shown in Figure 14 consists of two anaerobic ponds in parallel--a high-rate pond and a polishing pond. The anaerobic ponds have a surface area of 3.7 acres, a maximum depth of 3.0 feet, an average depth of 6.0 feet, and an approximate volume of 22.2 acre-feet. The detention time for the two anaerobic ponds (considering the 4.6 MGD flow or 14.1 acre-feet) is therefore 1.6 days. The aerobic high-rate pond (east pond) has a surface area of approximately 10.0 acres, an average depth of 3.5 feet, and a volume of 35.0 acre-feet. The calculated detention time for this pond is, therefore, 2.4 days. This high-rate pond is equipped with four high-volume, low-head pumps having a capacity of 18,500 gallons per minute for each pump. Although the design flow velocity was to be 0.5 feet per second in the channels, considering an average width of 85 feet, an average depth of 3.5 feet, and the fact that most of the time only two of the four pumps operate, the calculated average flow velocity is 0.275 ft/sec or 16.4 ft min. The surface area of the polishing high-rate pond (west pond) is 7.0 acres and the volume is 38.5 acre-feet (considering an average depth of 5.5 feet). The calculated detention time for this pond unit is 2.7 days. In this pond unit, usually all four pumps are in operation and the calculated velocity for this unit is 0.28 ft/sec or 16.8 ft/min when an average width of 80 feet is considered. The detention time for all of the three pond units together is 6.7 days. All of the above data are summarized in Table XII.

The average BOD level of the sludge-free effluent from the secondary clarifier (sampling point 2) is 20.0 mg/l; the average flow, 4.6 MGD; and the calculated BOD loading to the anaerobic pond unit is 210 lb/acre/day. The effluent from the anaerobic unit has a BOD level of 18.5 mg/l;

TABLE XII

Capacities, Detention Times, and BOD Loadings of the Concord Ponds

Pond	Surface Area (acres)	Depth (feet)	Volume (ac.-feet)	Detention Time (days)	BOD Load (lb/ac/day)
Anaerobic	3.7	6.0	22.2	1.6	210.0
High-Rate (east)	10.0	3.5	35.0	2.4	72.5
High-Rate (west)	7.0	5.5	38.5	2.7	34.0
Total	20.7		95.7	6.7	

Therefore, the BOD loading of the following aerobic unit was 72.5 lb/acre/day.

The BOD level of the aerobic pond effluent is 6.0 mg/l, and the related BOD loading of the polishing pond is 34.0 lb/acre/day. The yearly average BOD of the final effluent (after chlorination) to Walnut Creek is 5.2 mg/l. It should be noted that all of the above values for BOD are those of filtered samples, i.e., after the removal of the algae and some bacteria.

Pond Performance for the October 1968-November 1969 Period

In Table XIII are summarized the performance data of the pond system for the period starting in October 1968 and ending in November 1969. All BOD data, i.e., the yearly data as well as the data for the study period were determined from filtered samples. As seen from the table, the BOD reduction was from 20.0 mg/l at sampling point 2 to 5.2 mg/l at sampling point 5B. This is an overall reduction of 74%. Considering the low BOD level at sampling point 2, this is a satisfactory result.

The data for suspended solid concentrations do not indicate a reduction comparable to those of BOD. This difference may be explained by the fact that the suspended solids, as measured at sampling point 2 are the suspended solids from the secondary treatment plant effluent, and therefore includes organic matter basically sewage in nature. These organic solids are thereafter converted to algal cell material within the pond system. As a result, the suspended matter as measured at sampling point 5B is for practical purposes almost 100% algal cell material. This was also the case with the Richmond pond, as pointed out in a previous section of this dissertation.

The pH values were found to be extremely stable during the year

TABLE XIII

Analytical Data for the October 1968-November 1969 Period

Date	Flow in MGD[1]			BOD in mg/1			Suspended Solids in mg/1			pH at 1030	
	CCCCSD[2]	Concord	Total	Sampling Point			Sampling Point			Sampling Point	
				1	2	5B	1	2	5B	4	5B
1968											
10-9	--	3.23	--	--	55	3	--	58	32	7.4	7.4
11-4	--	3.22	--	--	34	8	--	41	36	7.5	7.5
11-18	--	3.22	--	--	10	8	--	36	23	7.5	7.5
12-5	--	3.75	--	--	25	15	--	62	21	7.5	7.8
12-26	--	3.75	--	--	31	11	--	40	22	7.5	7.7
1969											
1-8	2.12	5.64	7.76	191	23	7	164	36	18	7.4	7.4
2-13	2.77	6.63	9.40	--	28	7	--	58	24	--	7.4
3-5	1.90	6.25	8.15	--	7	5	--	10	16	7.3	7.8
4-10	1.30	4.78	6.08	140	8	3	100	14	37	7.5	7.9
4-24	--	4.78	--	177	7	3	105	22	34	7.4	7.9
5-8	1.14	5.19	6.33	174	10	5	111	23	22	--	7.8
5-28	--	5.19	--	182	23	4	106	25	24	7.4	7.7
6-12	1.10	4.77	5.87	136	18	3	110	33	29	7.5	7.8
7-21	--	4.42	--	142	10	--	112	28	15	7.4	7.6
7-31	1.01	4.42	5.43	150	33	--	123	43	31	7.5	7.7
8-15	--	4.43	--	178	20	1	192	22	38	7.5	7.4
8-28	0.98	4.43	5.41	162	11	2	173	16	41	7.6	7.6
9-10	0.96	4.40	5.36	75	8	4	182	25	30	7.5	7.5
9-22	--	4.40	--	93	5	2	178	17	18	7.4	7.4
10-8	0.98	--	--	186	33	2	157	21	23	7.4	7.3
11-3	1.01	--	--	--	--	--	--	--	--	--	--
Mean	1.39	4.57	6.64	152.8	20.0	5.2	139.5	31.5	26.7	7.46	7.60
SD[3]	0.60	0.94	1.45	35.8	13.0	13.1	34.9	15.1	7.8	0.07	0.19
CV[4]	0.44	0.21	0.22	0.23	0.65	2.52	0.25	0.48	0.29	0.01	0.02

[1] MGD - Million Gallons per Day

[2] CCCCSD - Central Contra Costa County Sanitation District

[3] Standard Deviation

[4] Coefficient Varience

for such a type of pond system (much more stable than expected). This pH stability has been further confirmed by additional pH measurements during the study period.

Study Procedures

The major study program started on October 23, 1969 and continued until December 6, 1969, although some samples were collected as late as June 1970. The sampling points as shown in Figure 14 were established by mutual agreement with Mr. K. B. Renkirt, Laboratory Chemist for Concord; these sampling points relevant to the quality changes on the pond surfaces were sampling points 1, 2, 3, 4, and 5. At a later date, two additional sampling points for depth profiles (points 3A and 5A) were added. These are also indicated in Figure 14.

The sampling dates for surface sampling were: October 21, October 30, November 6, December 2, and December 6, 1969. On November 6 and on December 2, depth profile samples were collected at the West pond (sampling point 3A), and on November 13, depth profile samples were collected at the East pond (sampling point 5A). For supplemental data, additional samples and readings were made on May 13 and June 17, 1970. Comprehensive sludge analyses and dissolved oxygen determinations were performed and secchi disk readings were also made.

As shown in Figure 14, the position of sampling point 1 is at the overflow structure just ahead of the by-pass line to CCCCSD. Sampling point 2 is located at the effluent channel of the secondary clarifier; sampling point 3 at the outlet from the two anaerobic ponds; sampling point 4 at the outlet from the high-rate pond (East pond); and sampling point 5 at the outlet from the polishing point (West pond) ahead of the chlorine contact basin. The three additional sampling points are sampling point 3A inside the high-rate pond (for depth profile sampling); sampling point 5A inside the polishing pond (also for depth profile sampling); and sampling point 5B at the outlet from the chlorine contact basin.

Temperature and pH measurements were made at the pond site and in the Concord Treatment Plant Laboratory. All other analyses of the samples were made in the Sanitary Engineering Laboratory at the Richmond Field Station. All the collected samples were first filtered. The filtrates and the nonfilterable material was analyzed as indicated in Table XIV.

Because of the importance of the nutrient relationship between carbon, nitrogen, and phosphate, the samples collected on December 2 and on December 6 were analyzed for organic and inorganic carbon. Carbon analyses were also made on the filtrates.

Study Results

General. The quality and characteristic of the liquid in the pond system (called filtrate in a sample from which algae have been removed by filtration) is apparently influenced by three major factors: 1) the changing characteristic of the influent, i.e., treated sewage from the secondary treatment plant; 2) weather and other climatic conditions; and 3) algal growth and the related processes occurring in the liquid of the pond system.

Pond Influent. The characteristics of the sewage at sampling point 2 were considered to be indicative of the influent to the pond system. This was valid as far as the present study is concerned, since changes in characteristics at sampling point 2 (mainly carbon, nitrogen, and phosphate concentrations) were found to influence the processes in the pond system.

TABLE XIV

Sample Analyses Conducted at the University of California Richmond Field Station

Date	Filtrate						Non-Filterable Material (mainly algae)						
	NH_3-N	Tot-N	$PO_4^{\equiv}$	Org C	Inorg C	Alk.	Tot S.S.	Vol S.S.	NH_3-N	Tot N	$PO_4^{\equiv}$	Org C	Inor C
Oct. 23	+	+	+				+	+					
Oct. 30	+	+	+				+	+					
Nov. 6	+	+	+				+	+					
Nov. 13			+				+	+					
Dec. 2	+	+	+	+	+		+	+	+	+	+	+	+
Dec. 6	+	+	+	+	+	+	+	+	+	+	+	+	+

Weather and Other Climatic Conditions. The differences in temperature between the October 30 sample (18.5°C) at the pond system effluent and the December 2 sample (13.0°C) was 5.5 degrees. In addition to this temperature change, changes in light conditions (because of shorter days and cloudiness) also occurred during the study period. The influence of such weather conditions is well illustrated in Figures 22 and 23 (for a cloudy day on December 6) in which the influence of weather conditions on algal growth and carbon intake are evident.

Algal Growth and Related Processes. Except for the December 6 sample which was taken on a cloudy day, samples were taken on sunny days for better comparison. Other influences of the climatic conditions (changing temperatures, day and night cycles, etc.) on algal growth are well known and will not be further described in detail. However, other phenomena related to algal growth, especially the chemical changes within the pond liquid and the mixing effect of continuous pumping and recycling are worth mentioning.

It has been reported by Oswald, et al. that in stabilization pond liquid, the algal fraction of the suspended solids increases with detention time and the "sludge" (non-algal from sewage origin) fraction decreases and approaches zero at detention times of approximately four days. At detention times greater than four days, organic matter from sewage origin no longer is found and practically all of the volatile suspended solids consist of algal cells. Accordingly, considering the mixing effect brought about by the operation of the pumps, it was assumed for this study and borne out by the results that the total suspended solids (non-filterable material) from sampling point 3 and onward consisted almost entirely of algal cell material.

Pond Performance During Study Period. Temperature and pH Readings. Temperature readings and mean temperature are summarized in Table B-1 ("B" indicates Appendix B) and are illustrated in Figure 15. Figure 15 shows a steady temperature decrease from October to December; and Table B-1 shows a temperature decline from sampling point 2 to samplint point 5. The steepest temperature decline occurred between sampling point 2 and sampling point 3, thereafter the decline was more or less gradual.

Figure 15 also illustrates the stability of the pH level as recorded throughout the study period. The stable pH level is also illustrated by the data in Table B-2. The pH values measured on December 6, 1969 (in a sample with a relatively low algal concentration - 70% of the mean concentration for the study period) which were higher than those measured on December 2, 1969 (in a sample with a relatively higher algal concentration - 92% of the mean of the study period) may be explained by the fact that there was a weather change and probably a time lag between the weather change, the algal growth, and the sampling time.

Nitrogen and Phosphate Removal. Figure 16 shows the nitrogen and phosphate changes for every sampling day. Figure 17 depicts the mean values for the study period. Both figures show an apparent increase in ammonia, nitrogen, and phosphate concentrations between sampling point 2 and sampling point 3. The actual increases given in Tables B-3, B-4, and 5-5 are from 25.6 to 28.6 mg/l for total nitrogen (as N); from 20.5 to 23.6 mg/l for ammonia (as N); and from 10.8 to 12.1 mg/l for phosphate (as $PO_4^{\equiv}$). Although these increases could be due to errors, the reason for these seems to be that solids from the trickling filter were not fully settled and upon entering the anaerobic pond were decomposed to release ammonia or soluble

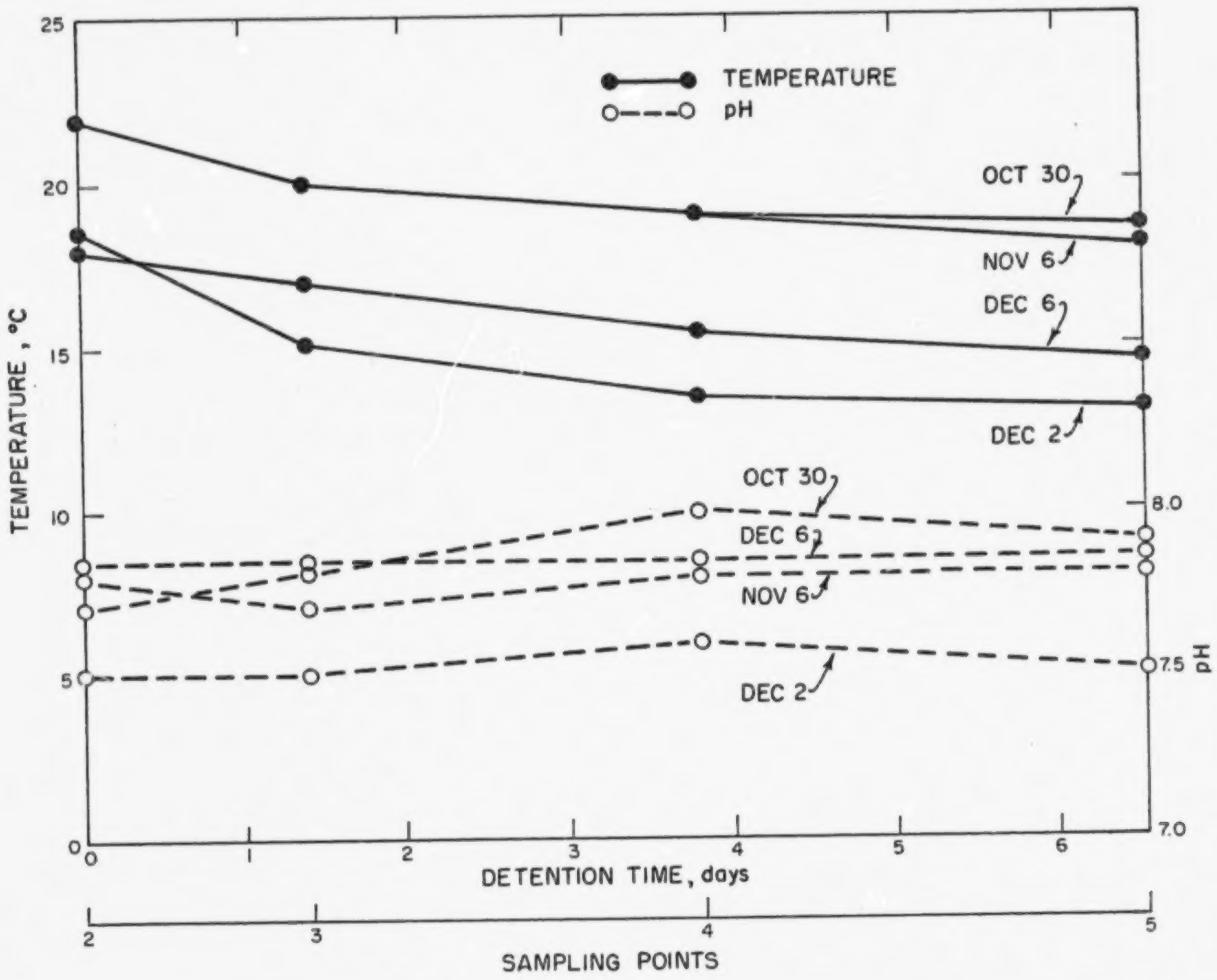

FIGURE 15. TEMPERATURE AND pH LEVELS

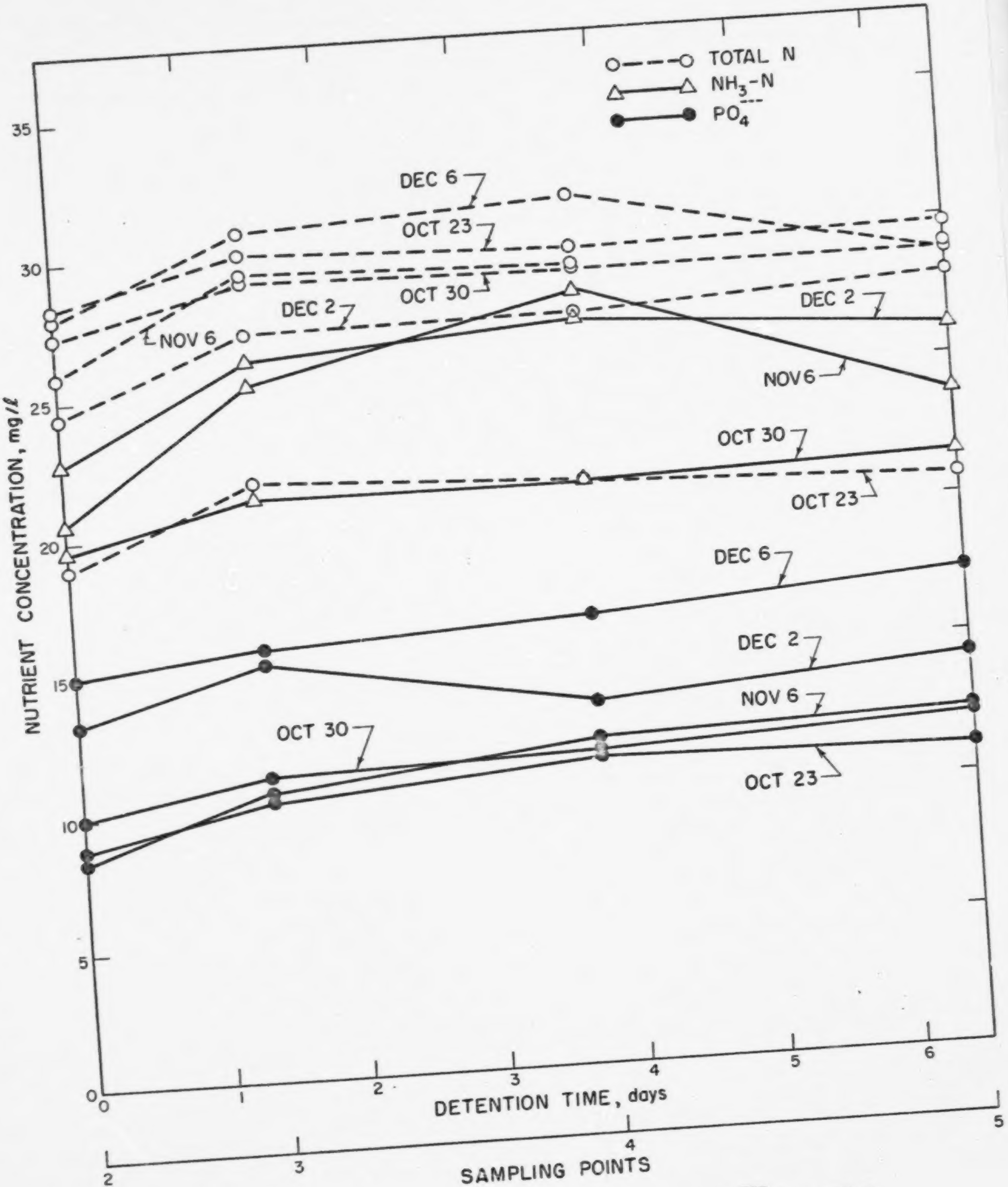

FIGURE 16. NH_3-N, TOTAL-N, AND PO_4^{---} LEVELS

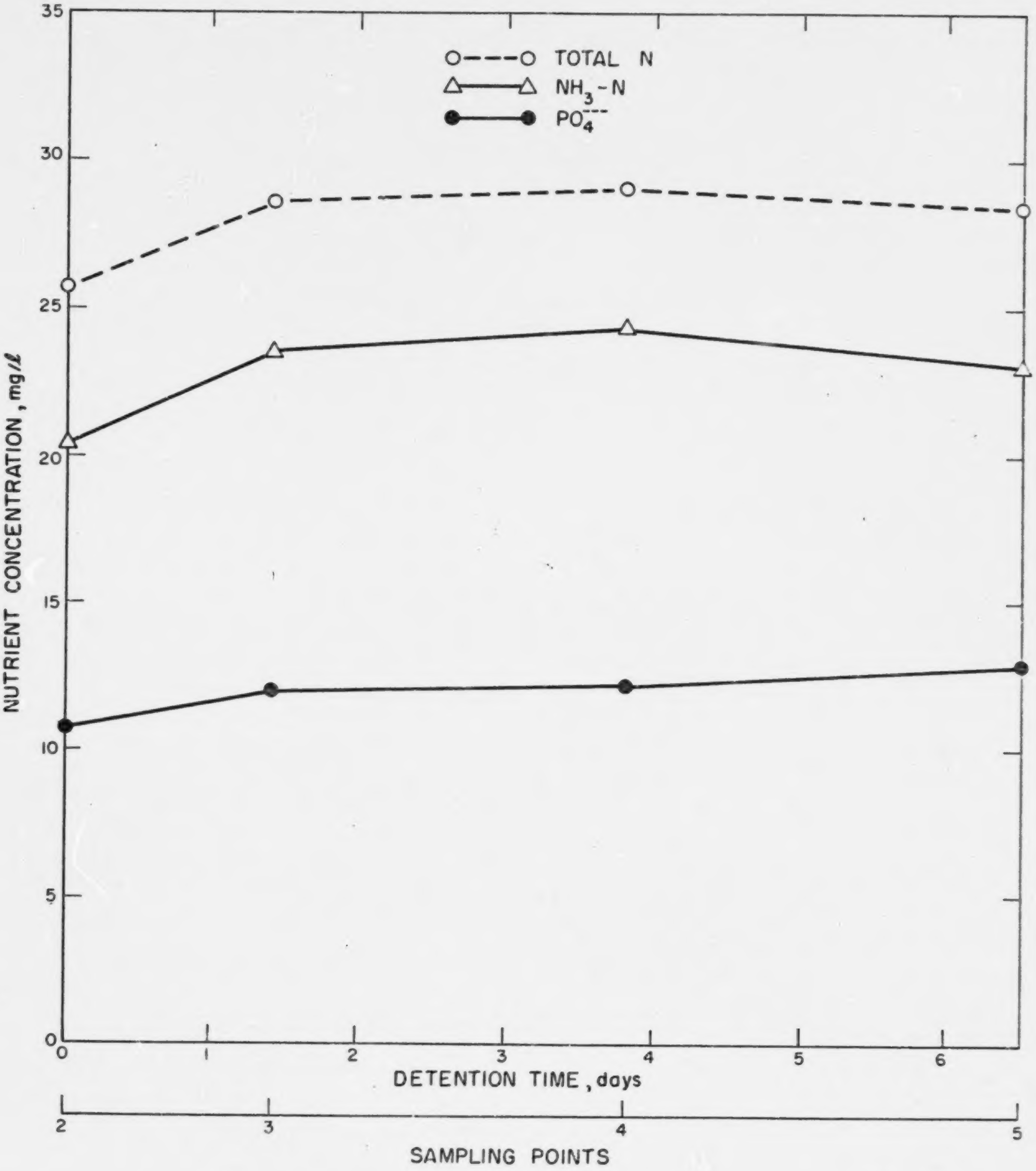

FIGURE 17. MEAN VALUES FOR NH_3-N, TOTAL N, AND PO_4^{---}

nitrogenous substances. This is possible because the suspended solids measured at sampling point 2 vary greatly and occasionally a large amount of solids may escape from the filter settling system. Such an input of solids could account for the differences noted. Similar findings were recorded by Parker (85) for the anaerobic units in the Melbourne stabilization pond system. Between sampling point 3 and sampling point 5 no change in the nitrogen concentration was recorded; however, a slight increase in phosphate concentration took place, as is clearly shown in Table B-5 and in Figure 17. A slight concentration effect due to evaporation would also exist but would be very small during the fall of the year.

Suspended Solids: A plot of all of the data for suspended and volatile solids, as well as those for ash can be found in Figure 18. The numerical data for the plotted points are shown in Figure 18 together with the mean values which are given in Tables B-6 and B-7.

As already explained, the suspended solid concentration from sampling point 3 and onward is considered to be algal in nature. It should be noted that the ash concentrations in these samples were in line with ash concentrations of algae generally reported in the literature. The general decrease in algal concentration from sampling point 3 toward sampling point 5 was expected, and accordingly the increase in algal concentrations found in the December 6 samples remains unexplained but probably was due to motile algae.

Depth Profiles of the High-Rate Ponds: Two depth profiles for sampling point 3A (in the middle of the East high-rate pond) are illustrated in Figures 19 and 20. The high suspended solids concentrations close to the pond bottom (at 3.0 feet depth), as well as the high carbon and dissolved oxygen concentrations at these depths should be noted.

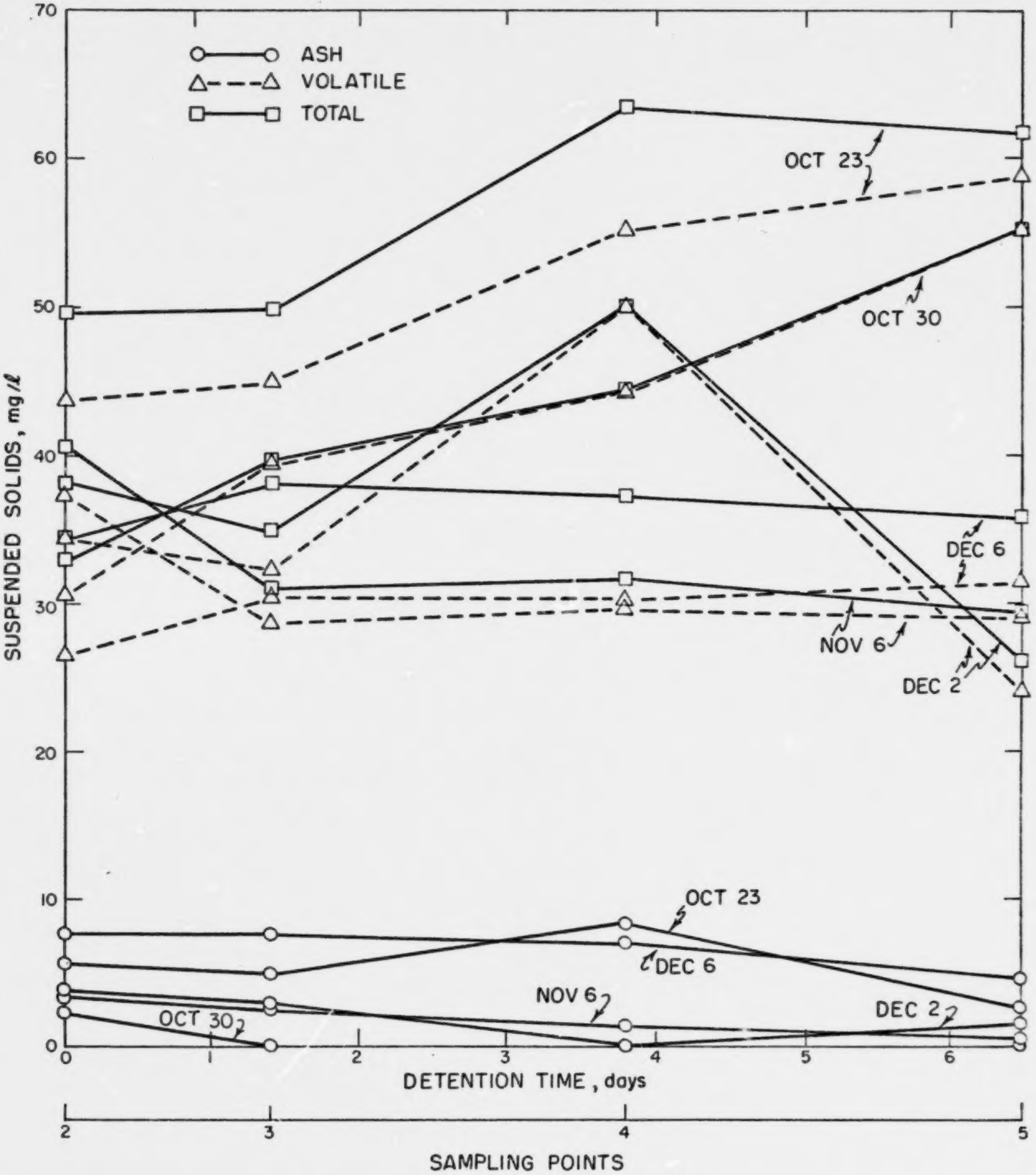

FIGURE 18. SUSPENDED SOLIDS IN POND LIQUID

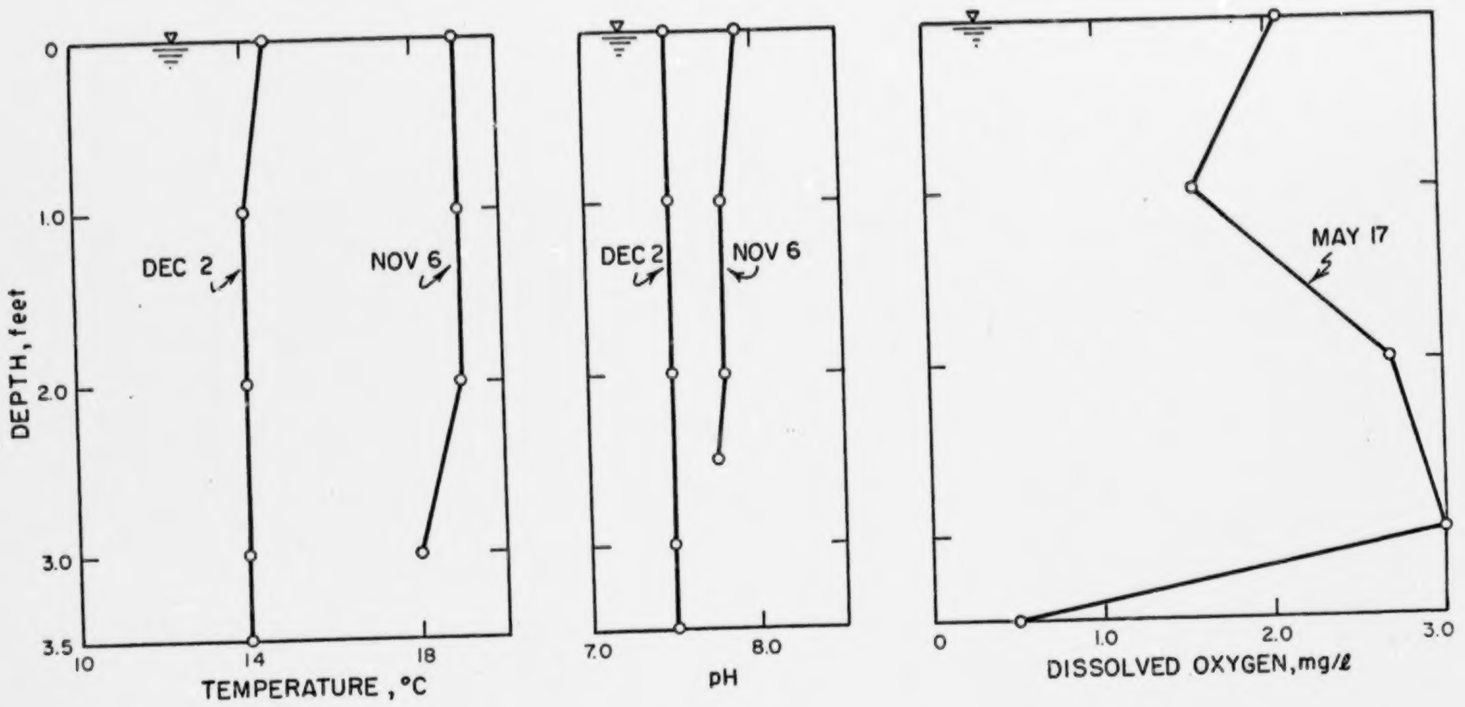

FIGURE 19 – DEPTH PROFILE FOR EAST POND, SAMPLING POINT 3A

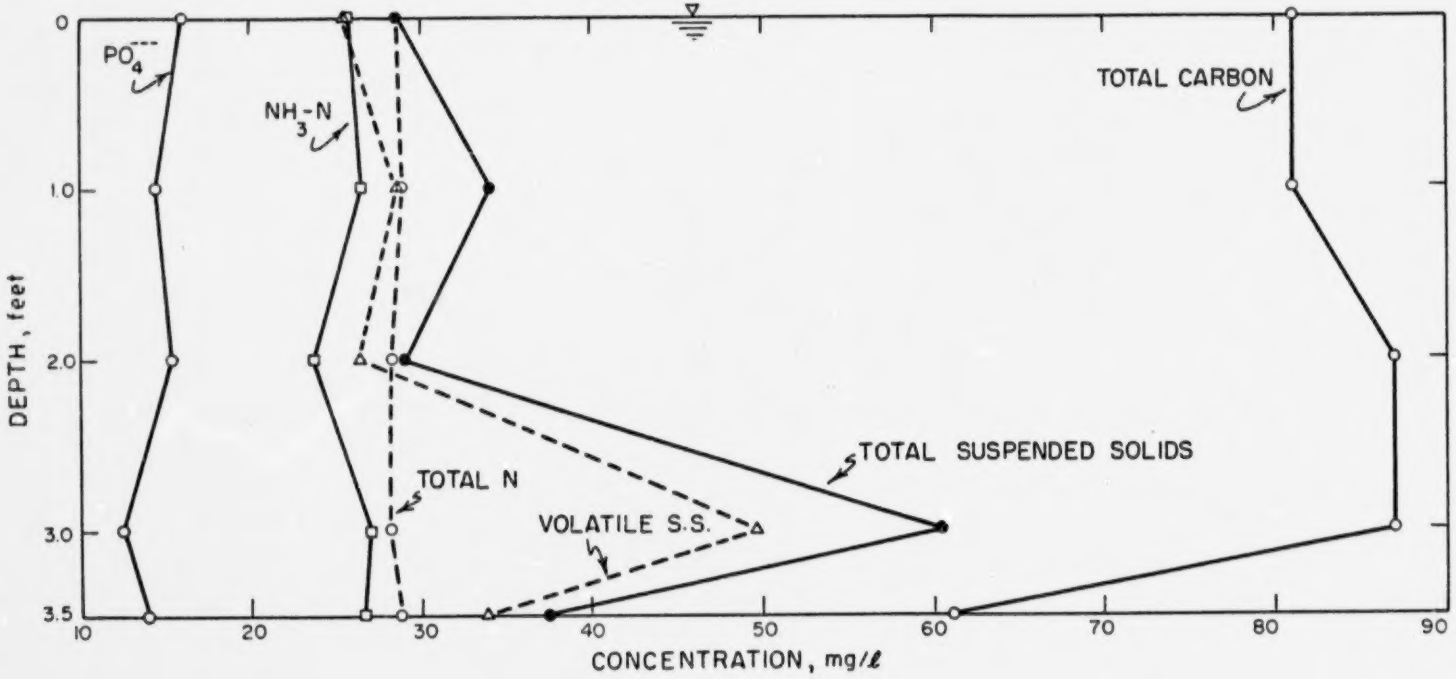

FIGURE 20 - DEPTH PROFILE FOR EAST POND, SAMPLING POINT 3A

A sample of the bottom sludge, including the dense algal population found there was examined under the microscope. As observed in this examination, the algal population consisted mainly of Chlorella sp. and Scenedesmus sp. An occasional blue-green alga was observed. However, the main bulk of the sample was composed of a very dense bacterial sludge having a brown-grey coloration.

The sludge sample was kept 24 hours in a quiescent condition so that the dense bacterial sludge could settle. Thereafter, the supernatent, which had a deep green coloration, was examined for algal concentration. The total suspended solid content of the supernatent was 564.0 mg/1, the volatile solids content representing the algae was 487.0 mg/1 or 87.2%, and the ash content was 77.0 mg/1 or 12.8%. The volatile solids in the settled sludge was 61.6% and the ash content 38.4%.

Based on a microscopic and analtyical examination of the high algal concentration adjacent to the pond bottom, it is assumed that the material examined was composed of three fractions: 1) settled algal cells, dead and alive, constituting the major fraction; 2) living algal cells actually growing in association with the sludge layer; and 3) some suspended inert material from the pond bottom.

An interpretation of this data indicates that the hydraulic velocity profile in the pond is such that a reduced velocity near the bottom permits entrapment of heavy algal and bacterial masses which, although partially suspended, remain near the pond bottom as they move along.

An additional depth profile was plotted for sampling point 5A at the polishing pond, which is 5.5 feet deep, as seen in Figure 21. In this pond high algal concentrations close to the bottom do not appear to be as high as in the East pond profile. Good mixing as indicated by almost

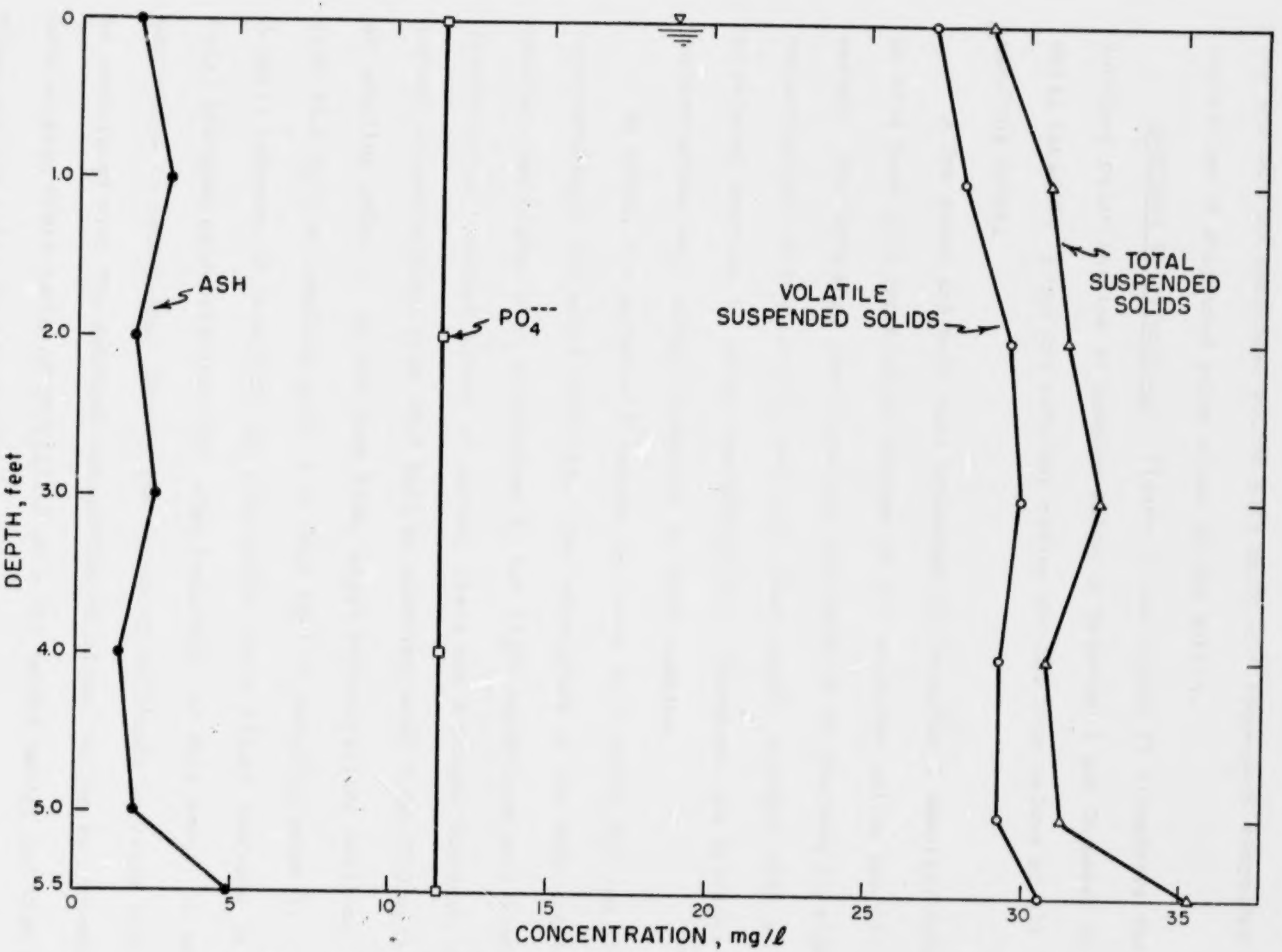

FIGURE 21 - DEPTH PROFILE FOR WEST POND, SAMPLING POINT 5A (Nov. 13, 1969)

unchanged suspended solids and phosphate concentrations (four pumps are continuously in operation in the West pond), seems to be an explanation for the uniform suspended solids with depth and consequent decreased concentration of suspended algae close to the bottom.

Nutrient Relationships: Figure 22 and Figure 23 illustrate the nutrient relationships of samples taken on December 2 and December 6; while Table XV gives the nutrient ratios for the mean values of all sampling dates.

A few sunny and warm days preceeded the December 2 sampling date. On this date good correlation between pH and suspended solids was observed. The favorable conditions are indicated by an increase in algal concentrations in the aerobic pond unit (East pond), together with a correlated decrease in carbon concentrations. Phosphate and nitrogen concentrations were almost unchanged in these samples.

As noted, the December 6 sample was teken on a cloudy day and with correspondingly low algal activity. The temperature of the pond liquid, however, was higher than on December 2, but light conditions were poor. Instead of an expected uptake of carbon, there was a slight increase in carbon concentrations, from 76.0 mg/l at sampling point 3 to 77.0 mg/l at sampling point 5. At the same time, algal concentrations declined from 38.2 mg/l at sampling point 3 to 34.6 mg/l at sampling point 5. A small increase in phosphate and alkalinity, and a slight decrease in total nitrogen concentrations were also recorded. At this point, it seems worthwhile to recall that ideally the uptake of nutrients by algae should be correlated with the nutrient composition of algae, having an approximate average C/N/P ratio of 100/12/2.5 on a dry weight basis; and that a favorable C/N ratio for algal growth in the pond liquid should, therefore,

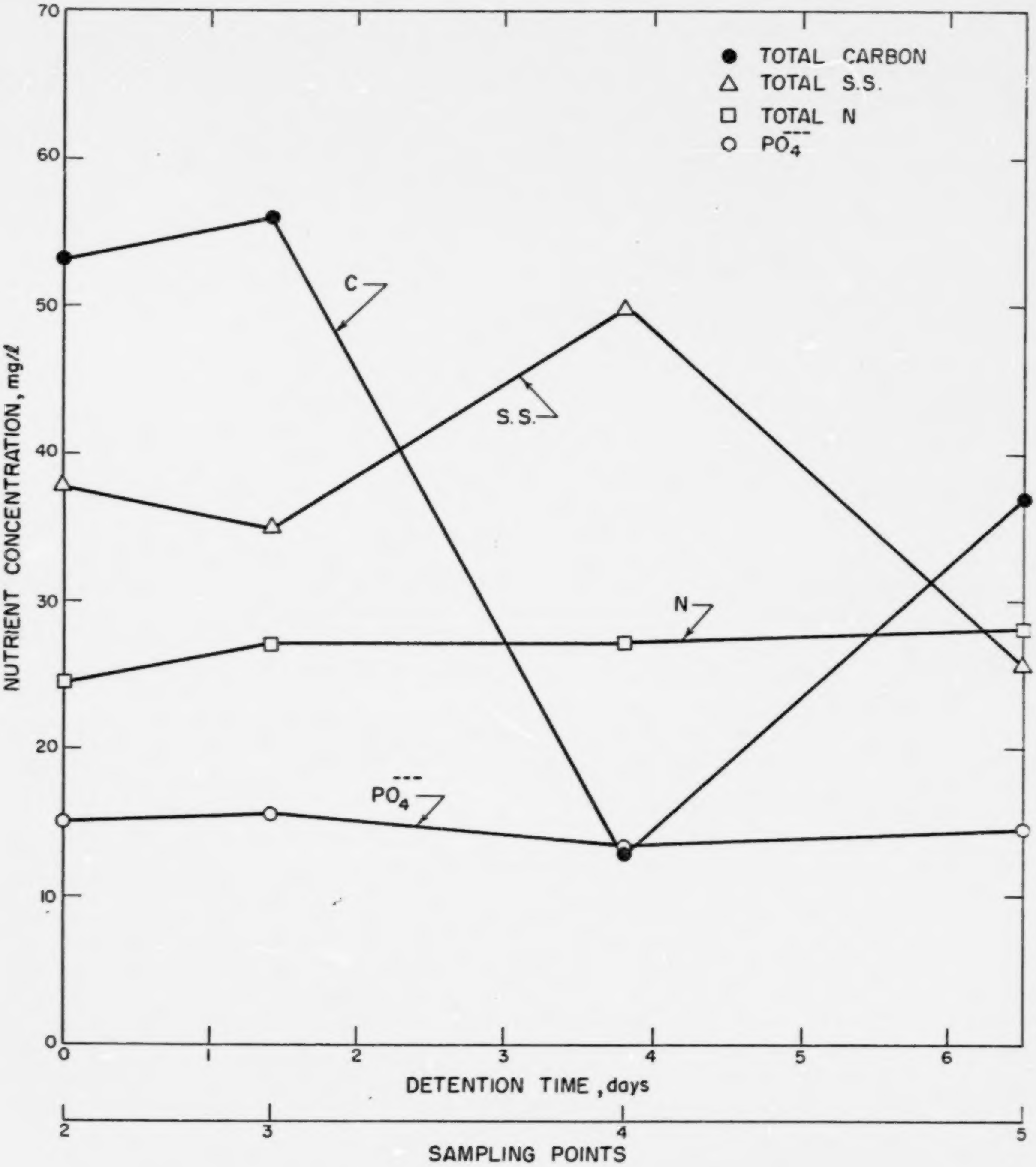

FIGURE 22. NUTRIENT RELATIONSHIP FOR SAMPLES TAKEN ON DECEMBER 2, 1969

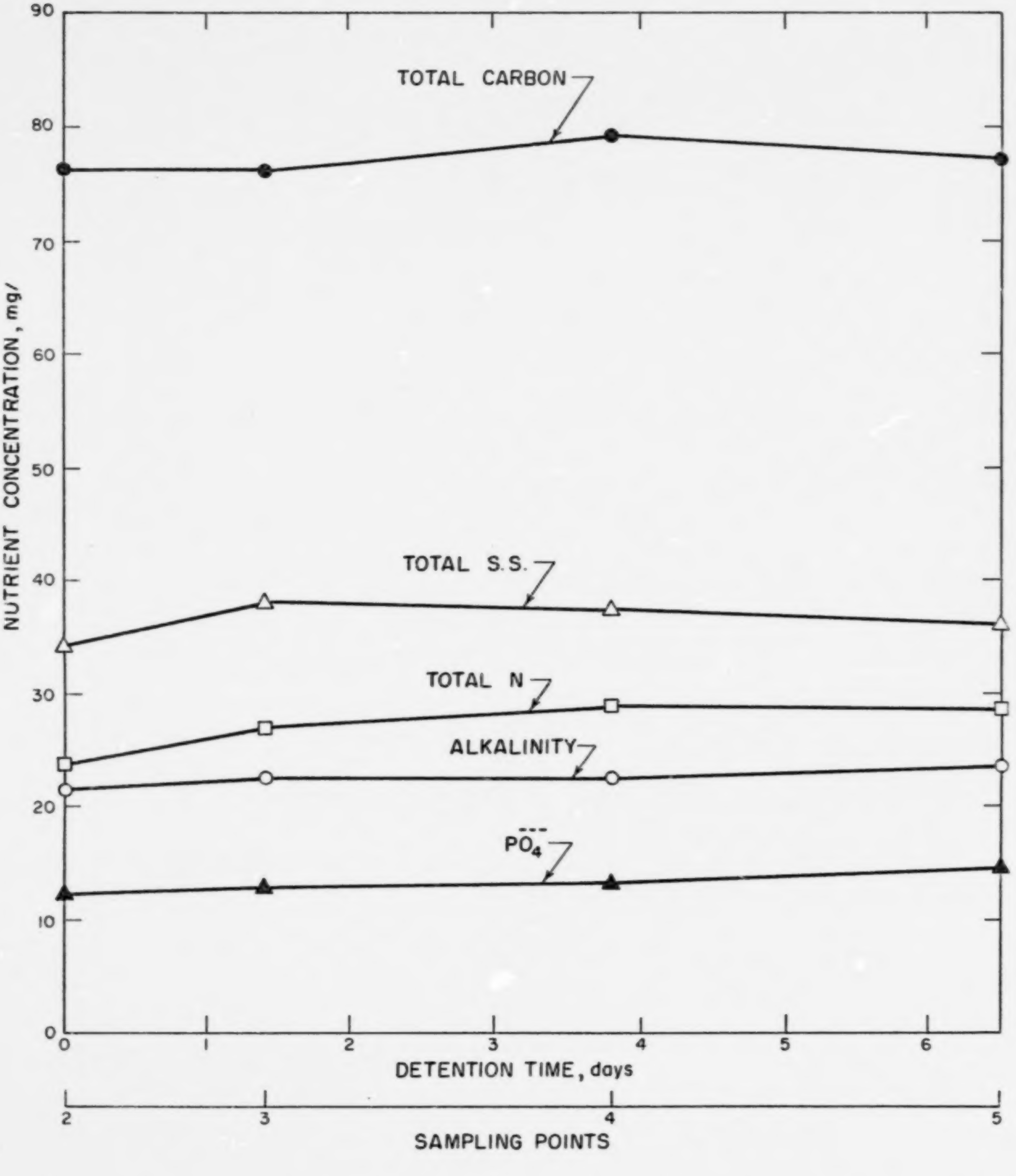

FIGURE 23. NUTRIENT RELATIONSHIP FOR SAMPLE TAKEN ON DECEMBER 6, 1969

TABLE XV
Nutrient Concentrations and Nutrient Ratios

Sampling Point	Nutrient Conc. mg/1			Nutrient Ratios		
	C	N	P	C/N	C/P	N/P
1	160.0	30.9	10.1	5.17	15.70	3.06
2	85.0	25.6	10.9	3.32	7.80	2.34
3	88.0	28.6	12.1	3.08	7.25	2.36
4	70.5	29.1	12.2	2.42	7.76	2.38
5	78.0	28.6	12.9	2.72	6.05	2.22

be approximately 100/12 or about 8.3/1, and a favorable C/P ratio should be approximately 100/2.5 or 40/1. By comparing these ratios with ratios given in Table XV it appears that a nutrient imbalance in the form of excess nitrogen or too little carbon occurs through the pond system is well demonstrated. Furthermore, this table shows that, because of some carbon uptake by algae with minimum corresponding nitrogen and phosphate uptake, the C/N and C/P ratios declined from sampling point 2 to sampling point 5.

Carbon Determinations: Detailed carbon determinations were made of the pond influent and of the pond liquid at all sampling points.

The percentages, together with the mean concentrations of the four carbon fractions are summarized in Table XVI, and are shown graphically in Figure 24. Tables B-8, B-9, B-10, B-11, and B-12 show the actual concentrations of the above-mentioned four carbon fractions. The low carbon concentration in the solid fraction of 24% in relation to the high concentration of the liquid fraction of 76% should be noted. This low solid portion of carbon together with assumed low solid portion of the other nutrient is believed to be responsible for the poor performance of the anaerobic pond unit.

The dip in the curves showing the dissolved carbon fractions at sampling point 4 may be related to a sampling or analysis error, and a straight line between sampling points 3 and 5 would probably be closer to the actual conditions. This possibly is supported by inspecting Figure 25, which illustrates the mean values for dissolved organic carbon, dissolved inorganic carbon, total carbon (T-C), COD, and alkalinity as a function of detention time.

The COD sampling results are given in Table B-13. For the reason

TABLE XVI

Percentage Carbon in the Dissolved Organic and Inorganic Portion and in the Suspended Solids of the Influent and Pond Liquid

Carbon Fraction	Sampling Point							
	2		3		4		5	
	mg/1	%	mg/1	%	mg/1	%	mg/1	%
Liquid-Dissolved Inorganic	42.0	49.4	45.5	51.7	26.5	37.6	37.5	48.1
Liquid-Dissolved Organic	22.5	26.6	20.5	23.4	19.5	27.7	19.5	25.0
Liquid-Subtotal	64.5	76.0	66.0	74.1	46.0	65.3	57.0	73.1
Solid-Inorganic	5.5	6.5	5.5	6.3	4.0	5.7	3.5	4.5
Solid-Organic	15.0	17.5	16.5	18.6	20.5	29.0	17.5	22.4
Solid-Subtotal	20.5	24.0	22.0	24.9	24.5	34.7	21.0	26.9
Total Carbon	85.0	100.0	88.0	100.0	70.5	100.0	78.0	100.0

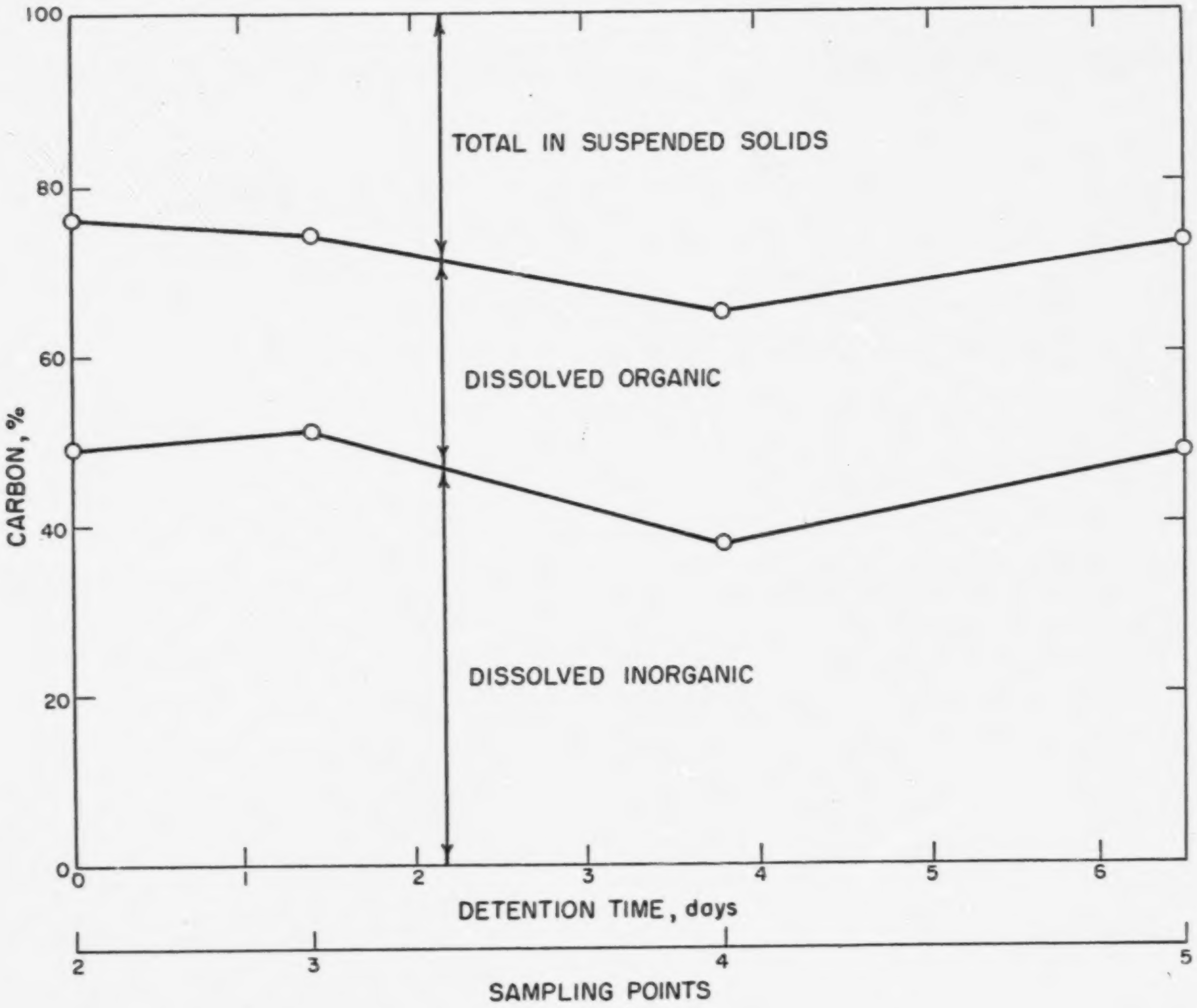

FIGURE 24. PERCENTAGE CARBON

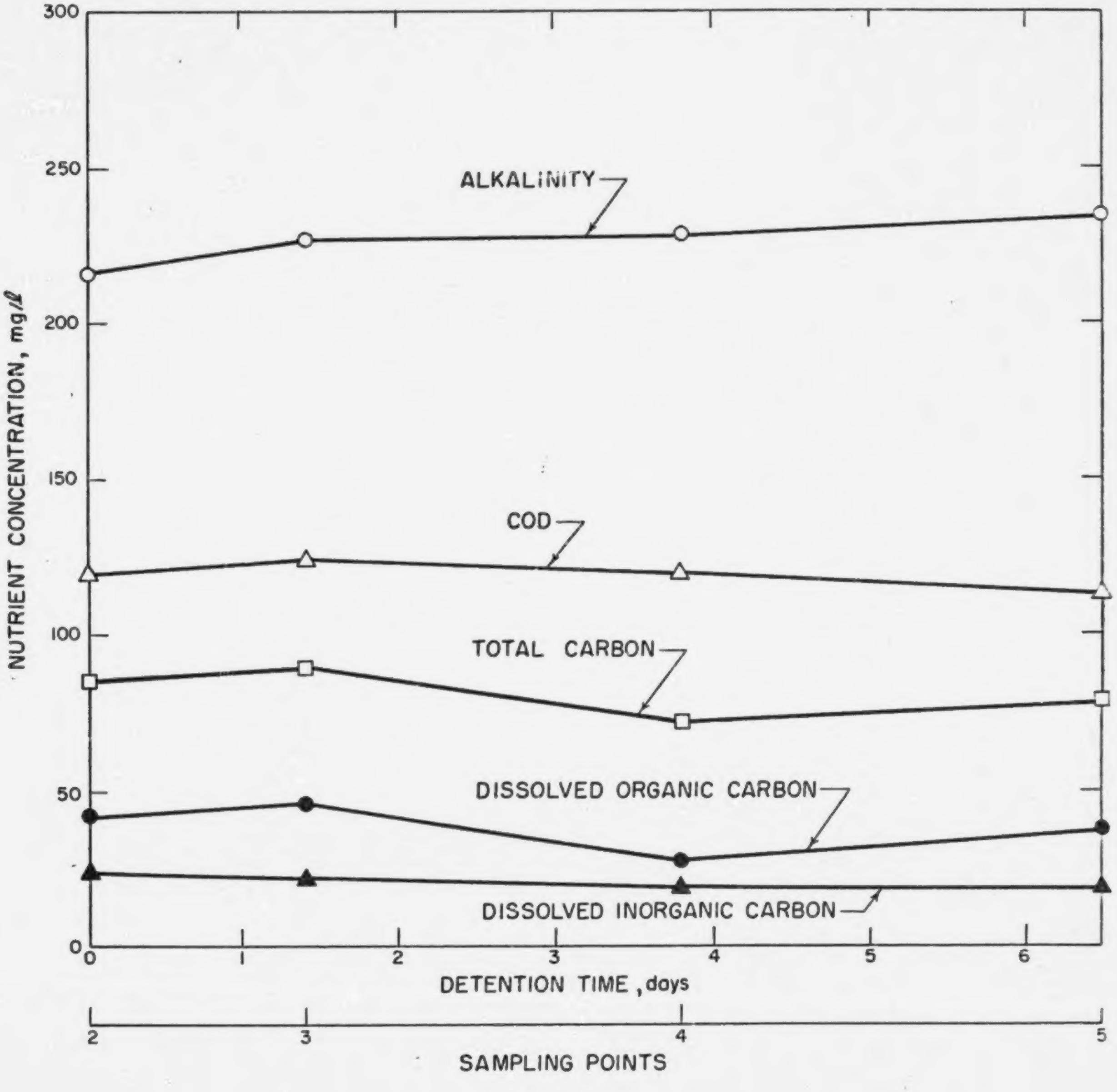

FIGURE 25. MEAN VALUES OF CARBON, COD AND ALKALINITY

that BOD analyses were made on one sampling day only, these results were not summarized in a table.

Sludge in the Unlined High-Rate Pond

As previously mentioned, over the years, the Concord pond had evidently developed a fairly well-defined, sludge-slime layer which is loose, flexible, and which apparently tends to prevent erosion of the unlined pond bottom. This sludge-slime layer seems to be well attached to the bottom soil. Because of the enormous cost of man-made pond linings, this phenomenon, if dependable, could constitute a substantial savings in high-rate pond construction costs. Microscopic and visual observations of the bottom sludge samples revealed some of the sludge characteristics. From the visual observation, it was learned that this was a well-bound, compact, slimy sludge mass with cohesive characteristics. Microscopic observations revealed that this sludge was composed of a clearly defined sludge mass around soil particles which seems to act as a nuclei for sludge formation. An amorphorus organic debris mass, presumably settling downward from the top of the pond, has also been observed. In addition, a relatively great number of bacteria, motile and nonmotile, and a great number of algae, living and dead, were found to be an integral part of the bottom sludge layer.

Figure 26 consists of two microphotographs of the bottom sludge. In the center of photograph A, a decaying Scenedesmus alga is shown. The two cell units at the right are at a high degree of decay and have started to integrate in the surrounding sludge. Two soil particles, to the lower left of the decaying Scenedesmus, can be seen imbedded in the bottom sludge.

Photograph B shows three larger soil particles (dark) imbedded into

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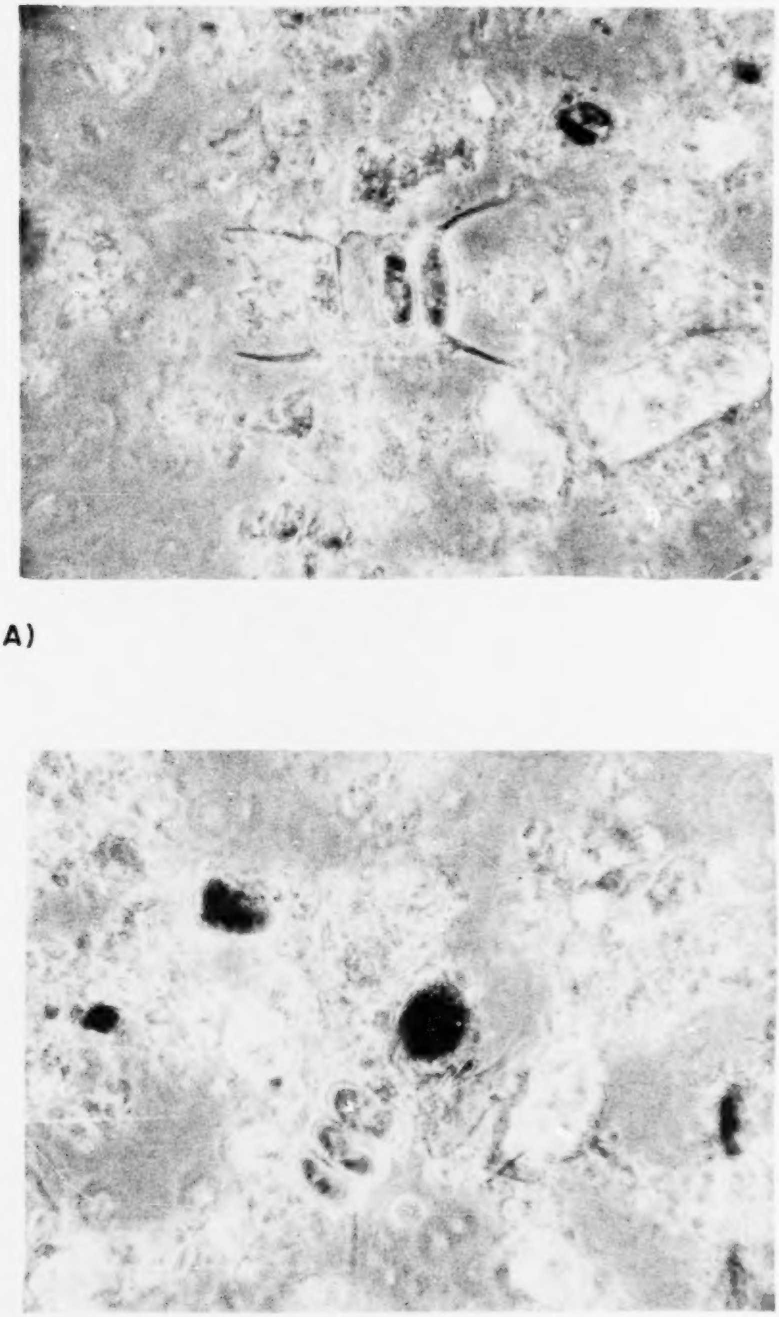

A)

B)

FIGURE 26. MICROPHOTOGRAPHS OF BOTTOM SLUDGE FROM AN UNLINED STABILIZATION POND (1000X)

the sludge (light) and a decaying Scenedesmus. At the center of the photograph and to the right of the big soil particle and the Scenedesmus, debris can be seen which is believed to have been organic.

The sludge layer of the unlined high-rate pond, no doubt, protects the pond bottom from erosion. In addition to protecting the pond bottom from soil erosion, the layer no doubt holds and protects the bacterial population from being swept away. Also, nutrient conversion probably occurs in the layer. According to McLaren (99), only 3 mm of sludge thickness may be needed to create anaerobic conditions. If this is true, it may be expected that in the sludge layer in the Concord pond which exceeds 3 mm in depth, bacteria release CO_2 and acid end-products into the pond liquid. The rate and amount of the releases in this unlined high-rate pond are not known, but they will undoubtedly depend on the amount of sludge and on the thickness of the sludge layer increasing as the sludge layer thickness increases.

Light-Box Studies

Nutrient removal AGP tests in light boxes were carried out on Concord effluents in January 1970. In these tests, the degree of nutrient removal from the effluent from the anaerobic pond and from the effluent of the high-rate pond was evaluated. In Tables XVIIand XVIIIare summarized the basic data as well as the results of the tests. The main objective of the tests was to find out if adjustment of the nutrient balance more nearly to correspond with the composition of algae could improve the nutrient removal rate by algae. It should be understood that in the control flask, the influence of more light energy for higher nutrient removal rates (higher than in the actual outdoor ponds) was tested. The tests with adjusted nutrient ratios, C/N values of 7.0 were made in order to

TABLE XVII

Light-Box Studies on Sample from Anaerobic Pond Effluent - Sampling Point 3
(in light-box from 1-13 to 1-16, 1970)

	Control				Sample Adjusted to C/N - 7			
	Start	End	Remov.	Remov. %	Start	End	Remov.	Remov. %
Inorg. Carbon mg/l	65	9	56	86.2	65	10	55	84.5
Organic Carbon mg/l	45	18	27	60.0	45	18	27	60.0
Total Carbon mg/l	110	27	83	75.5	110	28	82	74.5
Tot. Nitrogen mg/l	24.8	8.7	16.1	65.0	24.8	5.3	19.5	78.5
Phosphate mg/l	10.7	0	10.7	100.0	10.7	0	10.7	100.0
Tot. Sus. Solids mg/l	--	267	--	--	--	334	--	--
Sol. Sus. Solids mg/l	--	219	--	--	--	265	--	--
Fixed Sus. Solids mg/l	--	48	--	--	--	69	--	--
C/N	4.44	3.09	--	--	7.00	5.28	--	--
pH	7.7	10.6	--	--	6.5	10.7	--	--

Note: Acetic acid was added to pond liquid samples as a carbon source.

TABLE XVIII

Light-Box Studies on Sample from High-Rate Pond Effluent - Sampling Point 4
(in light-box from 1-13 to 1-16, 1970)

	Control				Sample Adjusted to C/N - 7			
	Start	End	Rem	Remov. %	Start	End	Remov.	Remov. %
Inorg. Carbon mg/1	70	23	47	67.0	70	18	52	74.2
Organic Carbon mg/1	50	9	41	82.0	50	18	32	63.8
Total Carbon mg/1	120	32	88	73.2	120	36	84	70.0
Total Nitrogen mg/1	26.0	12.3	13.7	52.5	26.0	6.7	19.3	74.2
Phosphate mg/1	11.40	0.04	11.36	99.7	11.40	0.02	11.38	99.9
Tot. Sus. Solids mg/1	--	--	--	--	--	--	--	--
Sol. Sus. Solids mg/1	--	186	--	--	--	250	--	--
Fix. Sus. Solids	--	--	--	--	--	--	--	--
C/N	4.61	2.61	--	--	7.00	5.36	--	--
pH	7.8	10.2	--	--	6.4	10.4	--	--

Note: Acetic acid was added to the pond liquid samples as carbon source.

find out if nutrient adjustment can further improve nutrient removal, i.e., further improve nutrient removal rate from those without nutrient adjustment but with additional light exposure (control flask). In such a test, 200 ml of filtered effluent was poured into each of the two test flasks, and carbon in the form of acetic acid (not neutralized) was added to one test flask to adjust the C/N ratio to 7/1. Thereafter, both test flasks were seeded with algae and put into the light box for four days. pH was not controlled during the experiment, and the rise in pH levels can be followed in Figure 29. Although four days is a short period for such a test, it clearly demonstrated the importance of carbon addition.

The experiment indicated that nutrient adjustment to a C/N ratio of 7:1 improved nutrient removal in the Concord anaerobic pond effluent. The increased nitrogen removed between the control flask and the flask in which the C/N was adjusted to 7:1 was 13.5% (from 65.0 to 78.5%--Table XVI; for the Concord high-rate pond effluent, the additional nitrogen removal was 21.7% (from 52.5 to 74.2%)--Table XVIII.

In the two tests, phosphate removals were much higher than the amounts of phosphate actually needed for algal growth (based on algal composition and related nutrient ratios). It was strongly suspected, as indicated above, that phosphate removal by precipitation had occurred in addition to any biological removal by algae which may have been involved. As a follow-up test, in order to prove this point, Richmond pond effluent with adjusted pH levels from 7.65 to 11.0 was tested in the dark. In the dark neither photosynthesis could take place nor could biological uptake by algae occur. The results as shown in Figure 27 in which it is clearly indicated that phosphate precipitation in Richmond waste began at pH levels of approximately 9.0 and all the phosphate precipitated out at pH levels of approximately 10.5. Presumably Concord waste samples would show this same effect.

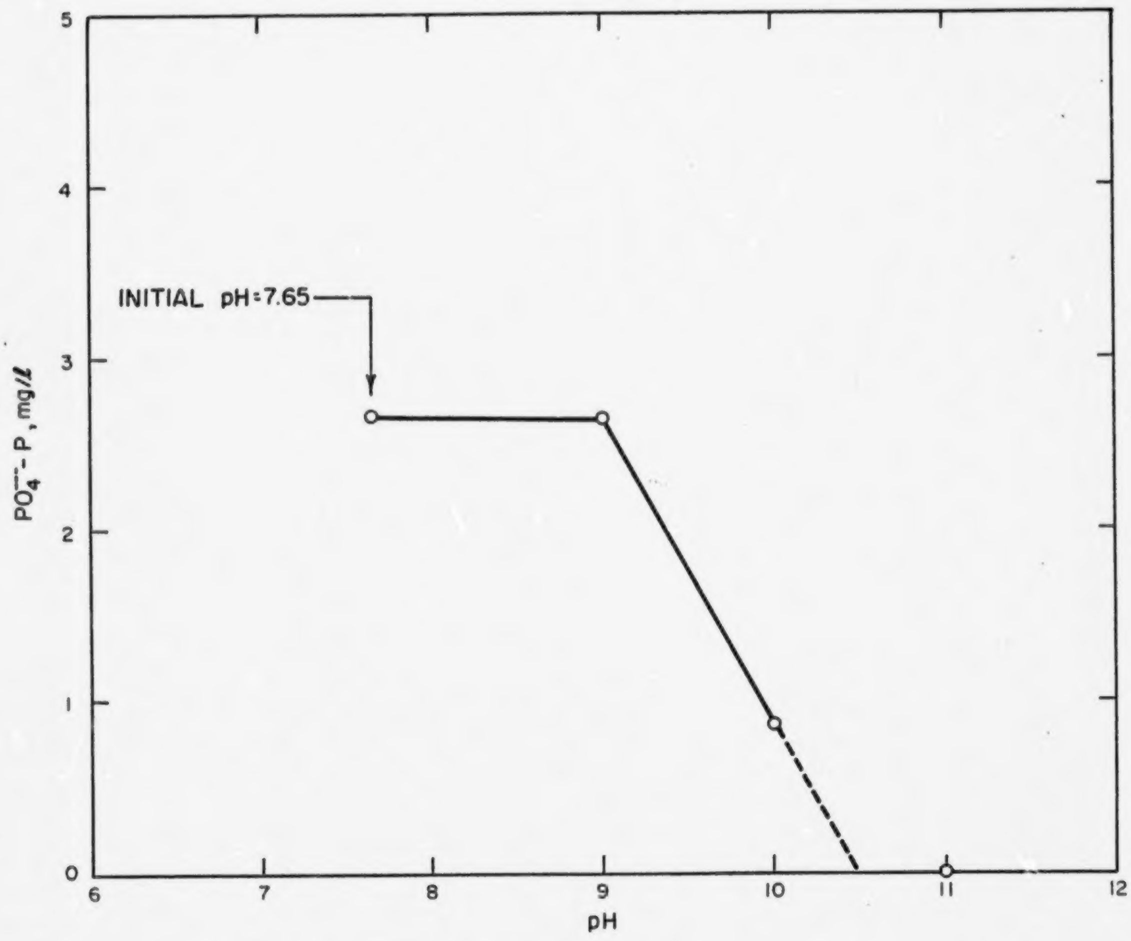

FIGURE 27.- PHOSPHATE PRECIPITATION AS A FUNCTION OF pH LEVEL

Supplemental Carbon Sources

As described in the previous section, the addition of carbon to the pond effluent enhanced the removal of nitrogen, and the question arose: What type of carbon compound could be used as a practical supplemental carbon source for ponds?

Because short-chain carboxylic acids (fatty acids) would be easily broken down by bacteria and would also be inexpensive (from time to time they are available as waste products from industrial plants), they seemed to be a good material to test as a source for carbon. Consequently, three carboxylic acids were tested. These three acids were: 1) formic acid with one carbon atom; 2) acetic acid with two carbon atoms; and 3) propionic acid with three carbon atoms. Because the low pH values associated with these acids could be harmful to algae as compounds or because of their acidity, they were neutralized before the algal inoculum was poured into the test flask. Acetic acid was tested once with neutralization and once without neutralization. In addition to the carboxylic acids, bicarbonate was tested as an inorganic carbon source by adding sodium bicarbonate to a flask filled with Richmond pond effluent.

The results of these four tests are shown in Figures 28, 29, 30, and 31. These four figures present results which indicate that the carboxilic acids were not desirable carbon sources either directly or indirectly for algae. At low concentrations, up to 15×10^{-5} moles there was some uptake, but concentrations above this level seemed to be toxic to algae.

On the other hand, the uptake of bicarbonate increased with concentrations as shown in Figure 31, and in combination with Richmond waste, bicarbonate proved to be by far the best carbon source tested.

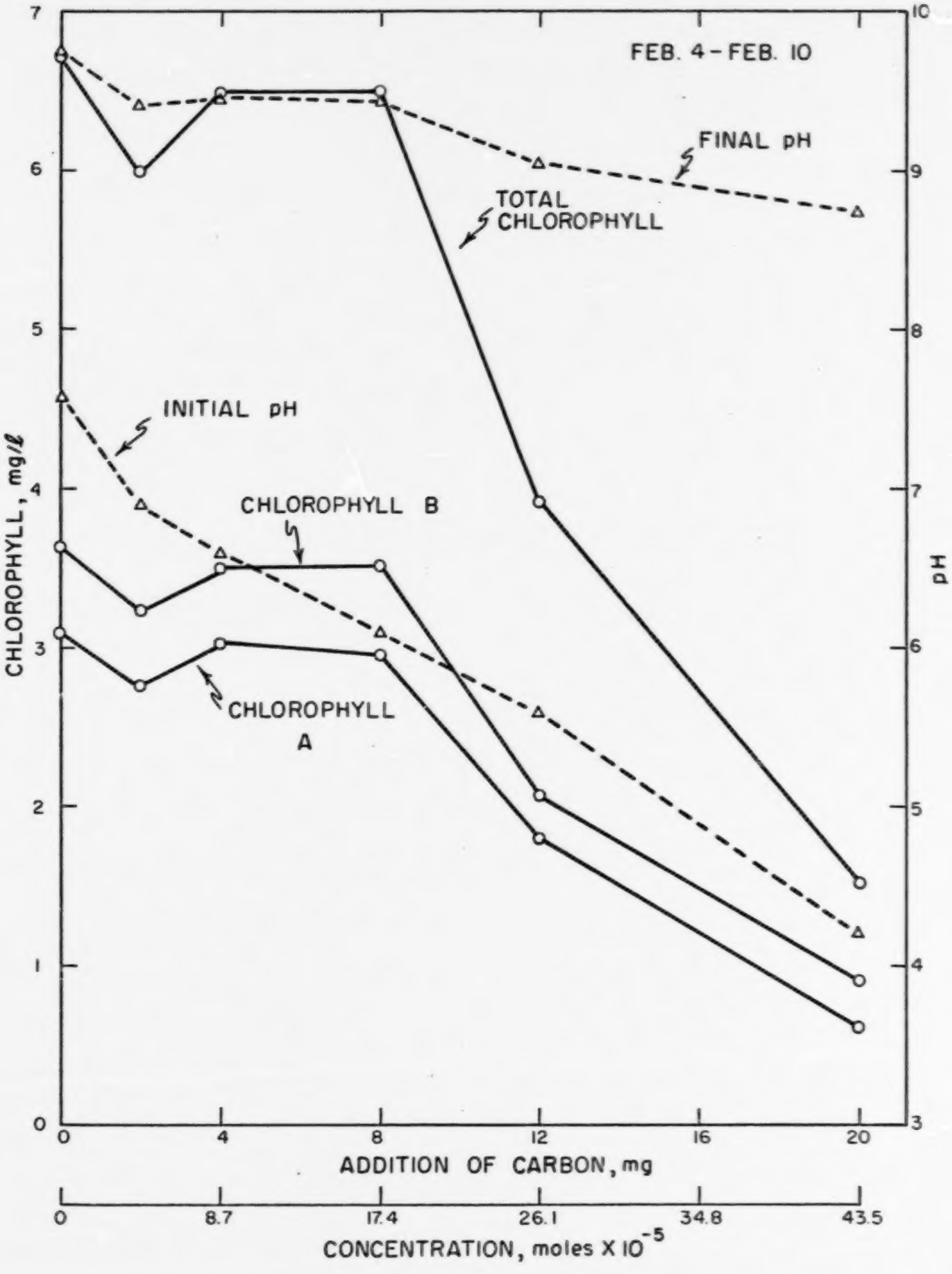

FIGURE 28.- ADDITION OF FORMIC ACID (NEUTRALIZED)

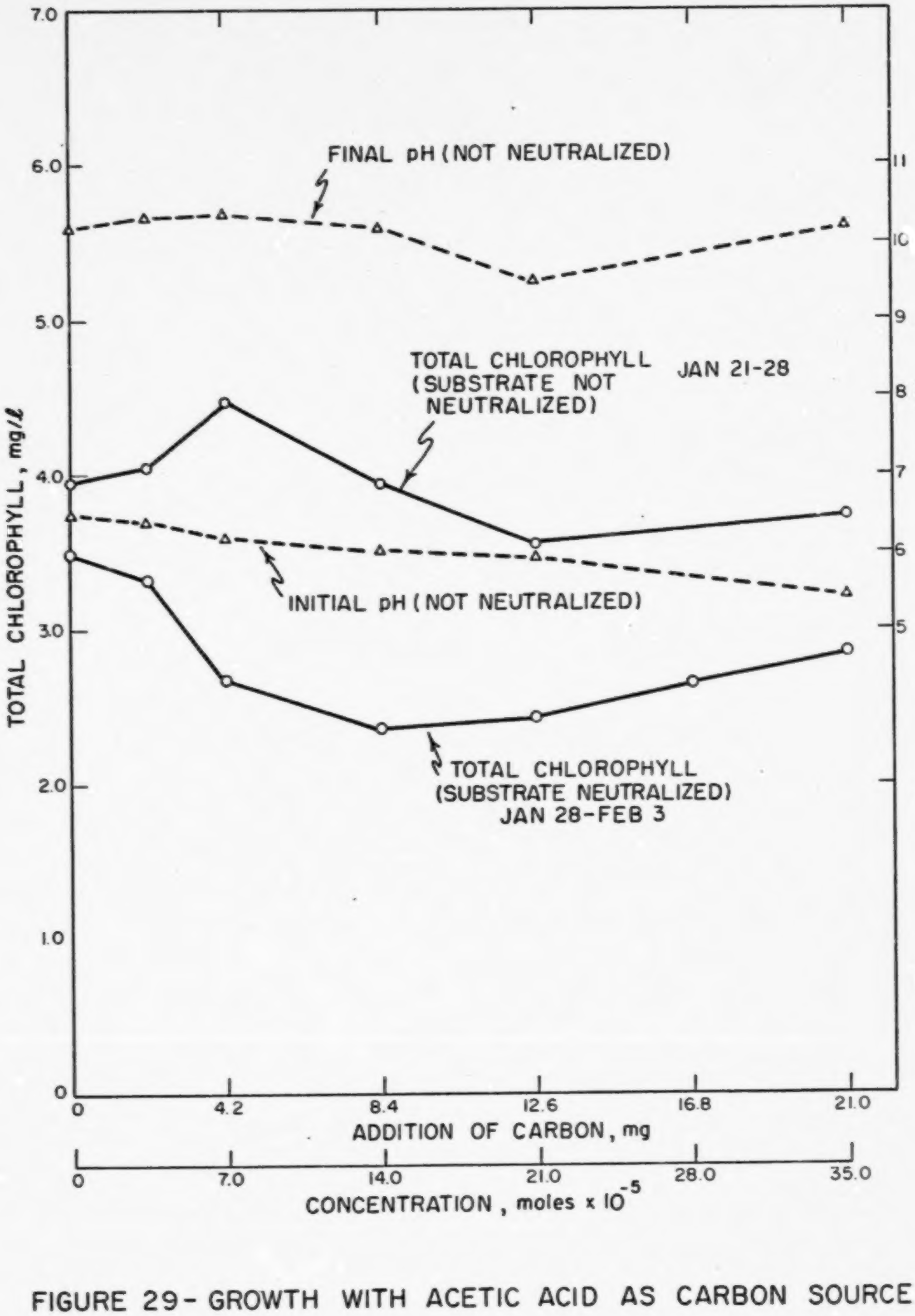

FIGURE 29- GROWTH WITH ACETIC ACID AS CARBON SOURCE

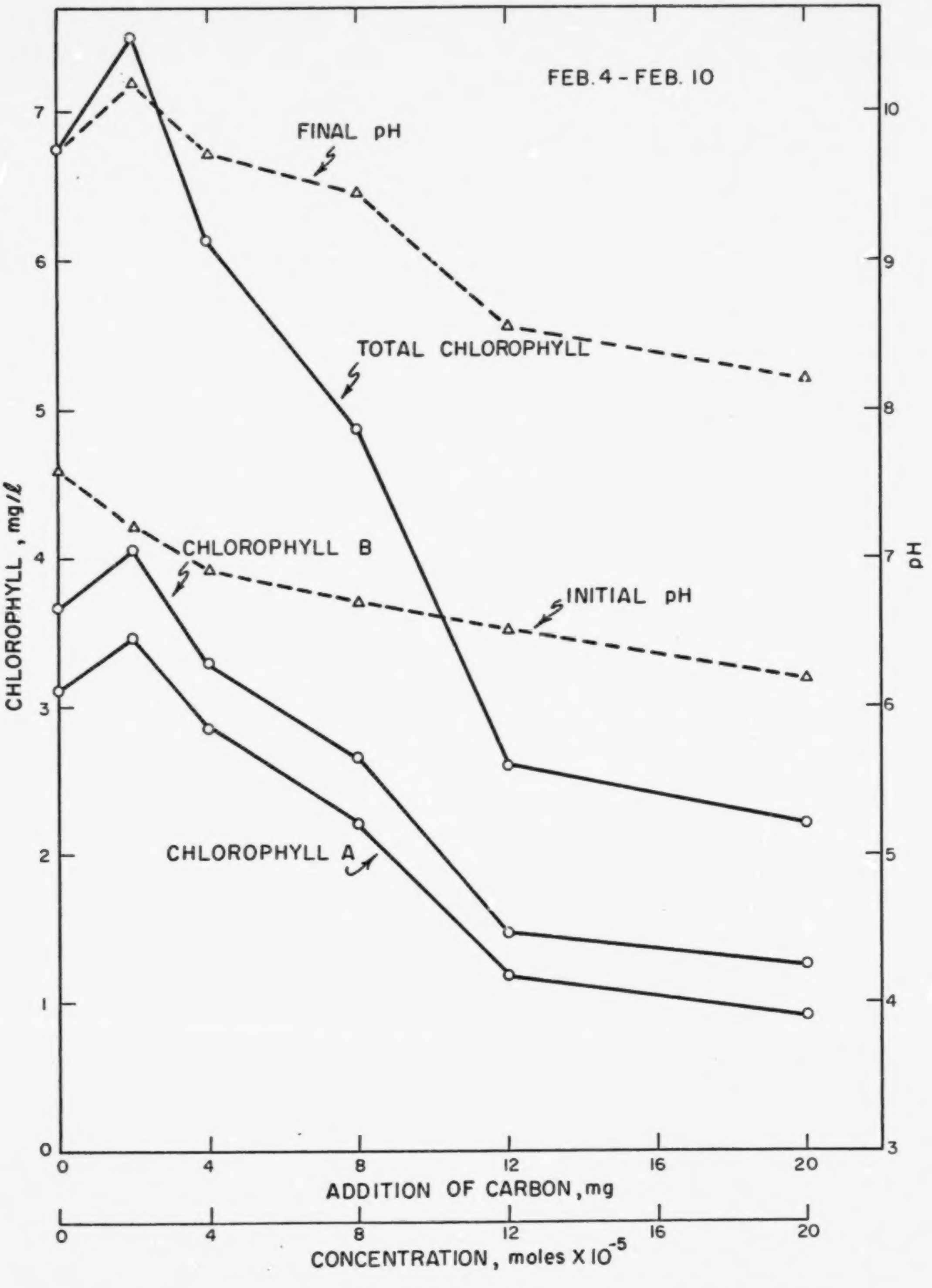

FIGURE 30 - ADDITION OF PROPIONIC ACID (NEUTRALIZED)

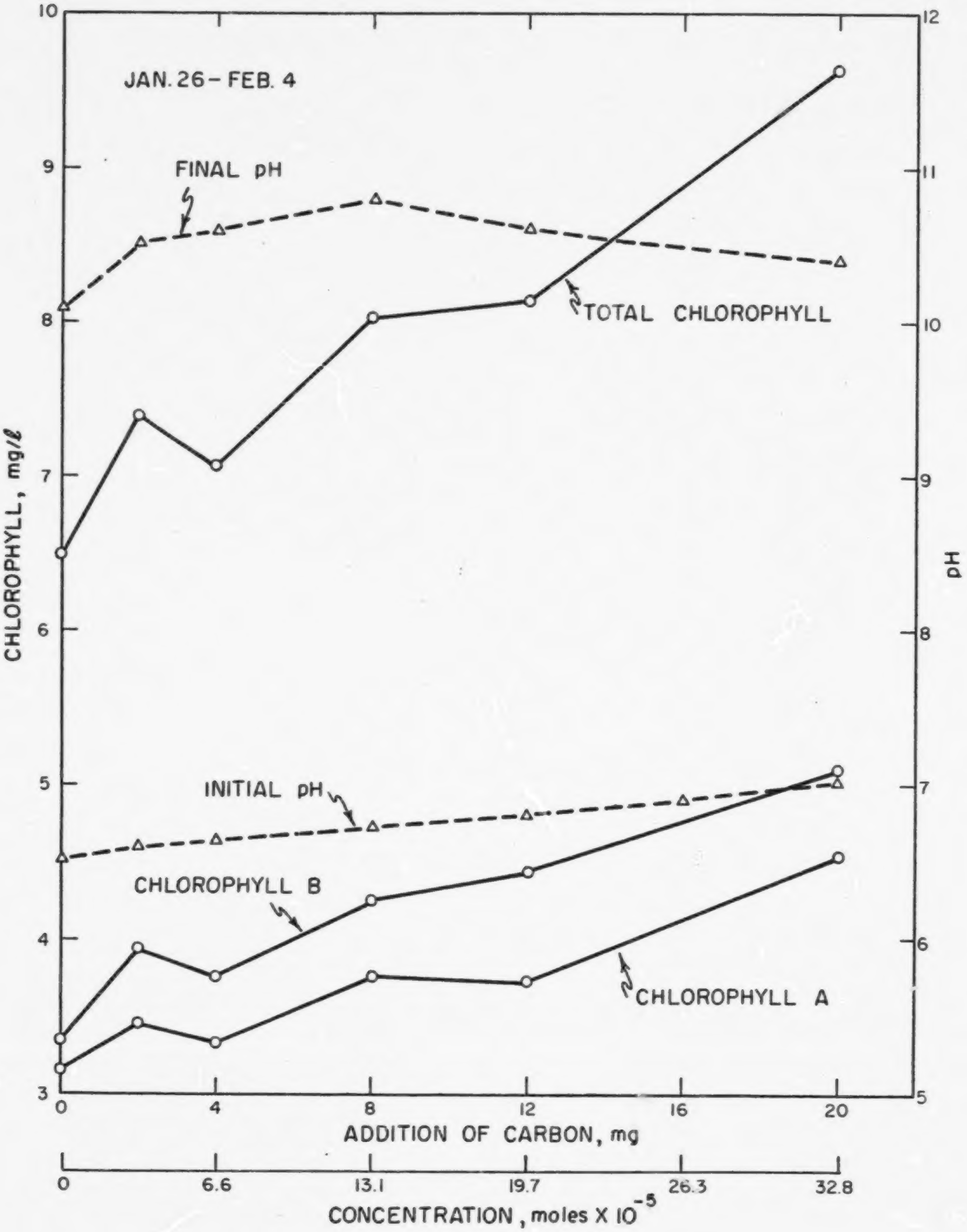

FIGURE 31 - ADDITION OF BICARBONATE

The tests on carbon sources indicated that in the present study, the algae while carrying out photosynthesis need an inorganic carbon source. Certain organic carbon sources can be used in "dark metabolism," i.e., under heterotrophic growth conditions providing oxygen is available to support an oxidative metabolism. Carboxylic acids did not break down as quickly as anticipated in the experiments (the reason seems to be that little oxygen or insufficient surface areas or time were available for bacterial action, and that the pH levels were too high). In addition, it was found that the undissociated acid molecules gave better results than the corresponding anions as shown in Figure 29. Samejina and Myers experienced similar results (102).

Algal Counts and Algal Identification

On August 31, 1970 algal counts and algal identifications were made in the Concord system to supplement earlier observations.

Sampling point 4: The volatile solid concentration was 30.6 mg/1 (the mean of the fall sampling period was 41.9 mg/1) and the total algal count was 8.9×10^3. The algal genus distribution at this count was: *Chlorella*, 5.6×10^3; *Chlamydomonas*, 2.2×10^3, *Ankistrodesmus*, 1.1×10^3; total, 8.9×10^3.

Sampling point 5: The volatile solids concentration was 50.5 mg/1 (the mean for the fall sampling period was 39.7 mg/1) and the total algal count was 2.34×10^4. The algal genus distribution for this sampling point was: *Scenedesmus*, 4.4×10^3; *Euglena*, 1.1×10^3; *Pediastrum*, 7.8×10^3; motile form (not identified), 3.3×10^3; *Chlorella*, 1.1×10^3; and chlorelloid forms, 5.6×10^3; total, 2.34×10^4.

Reasons that may be advanced for the algal population shift between the East high-rate pond (sampling point 4) and the West polishing pond (sampling point 4) are: 1) Differences in environmental conditions arising from differences in pond structure; 2) Change in nutrient composition and availability because of progressive decomposition of wastes as they progress through the pond system.

Treatment Efficiencies

The treatment efficiency of the pond system was evaluated for overall BOD removal (related to organic carbon removal) and for light conversion efficiency. Nutrient removal was not accomplished in the Concord system because nitrogen and phosphate actually increased slightly through the ponding system. Hence, treatment efficiencies for these nutrients were negative or indeterminant.

BOD Removal. The fact that the City of Concord had an active monitoring program for several years prior to this study made possible an evaluation of average overall BOD removal in ths system, and hence an evaluation of the overall deoxygenation constant. Inasmuch as data is only available at sampling point 2 and samplint point 5B, only overall values can be obtained. Data for the pertinent period between October 1968 and November 1969 shown in Table XII were used to calculate approximate removal values and K values.

In the approximated classical BOD expression:

$$Y = La\ (1 - 10^{-Kt}) \qquad (4\text{-}1a)$$

is modified slightly to incorporate data for the change in BOD between points 2 and 5B as follows:

$$Y_2 - Y_{5B} = Y_2\ (1 - 10^{-K^1\ T^1})$$

$$\text{or} \quad \frac{Y_2 - Y_{B5}}{Y_2} = (1 - 10^{-K^1\ T^1}) \qquad (4\text{-}1b)$$

in which Y_{5B} and Y_2 are the 5-day BOD values between points 2 and 5B,

½ is the 5-day = BOD at 2, K is the deoxygenation constant between the two ponds. With these assumptions and through substitution of data from Table XII, one can obtain a minimum K value of .0145, maximum K values of 0.194, and a mean K value of 0.087. The calculation of the mean K value of 0.087 is given as follows:

In the following calculation, only the generally measured 5-day BOD (Y = 5 days) will be used.

$$0.74 = 1.00\ (1 - 10^{-K6.7})$$

$$10^{-K6.7} = 0.26$$

Let K6.7 be x

$$10^{-x} = 0.26$$

$$\frac{1}{10^{x}} = 0.26$$

$$\frac{1}{0.26} = 10^{x}$$

$$x = \log 3.84 = 0.584$$

$$0.584 = 6.7K \quad \therefore \quad K = 0.087.$$

These values are low but are of the order of magnitude expected for the temperatures obtained and in view of the stability of the material being oxidized.

Light Conversion Efficiency. Light conversion efficiency was calculated according to the equation developed by Oswald (95).

$$h\ C_c = F\ S\ \frac{10}{d}\ \theta \qquad (4\text{-}2a)$$

and

$$F = 0.1\ \frac{h\ C_c\ d}{S\ \theta} \qquad (4\text{-}2b)$$

The meaning of the symbols in this equation are:

Symbol	Meaning	Units
h	Heat of combustion of algae	gr calories per mg of algae
$\Delta \hat{C}_c$	Increase in concentration of algae between sampling points	mg/liter dry weight

Meaning of symbols (cont.)

Symbol	Meaning	Units
F	Light conversion efficience	Percent of visible light
S	Solar radiation input between points	gr/calories/cm^2/day
d	Depth of pond	cm
θ	Detention time between sampling points	days

The heat of combusion, h, is generally 6 gr calories per mg of algal volatiles (95). The average solar radiation, S, for the months October, November, and December for the Concord location is approximately 125 gr/calories/cm^{2}day. The mean algal concentrations (volatile suspended solids) as shown in Table B-7 were 41.9 mg/l for the high-rate pond (East pond), and 39.7 mg/l for the polishing pond, which is also a high-rate pond. The depth of the East high-rate pond is 3½ feet or 106.0 centimeters.

Introducing these values into the above equation (4-2) one may calculate the overall light efficiency, F, for the East pond to be:

$$F = 0.1 \left(\frac{6 \times 41.9 \times 106}{125 \times 2.4}\right) = 8.85\%$$

For this efficiency and solar energy input, oxygen production is 250 lbs. per acre per day.

As previously stated, there was a decrease in the mean algal concentration between sampling point 4 (high-rate pond) and sampling point 5 (polishing pond). In other words, the ΔC_c value was -2.2 mg/l. If this negative ΔC_c value is introduced into equation (4-2), a negative light conversion efficiency would be indicated. If this is true, algae from the East pond were oxidized and/or decomposed in the West pond (see Figure 26).

Inasmuch as there was a real decline in algal concentration, the photosynthetic efficiency was negative in going from the East pond to the West pond.

Discussion

From the data presented for the Concord ponding system, it can be seen that the system effectively removed BOD in a relatively short detention time, but failed in the removal of nitrogen and phosphate. On an overall yearly basis, from 152.8 mg/l to 20.0 mg/l of BOD is removed by the primary and secondary treatment process. Thereafter, the BOD is further reduced by the pond system to a level ranging from 1 mg per liter to 15 mg per liter and averaging 5.2 mg/l at the effluent end.

Nitrogen and phosphate removals, measured during the sampling period, were quite different. The total nitrogen concentration at the influent was 30.9 mg/l. This concentration was apparently reduced to 25.6 mg/l at the treatment plant, but increased again in the pond system and reached a 28.6 mg/l level at the effluent (at sampling point 5). Phosphate concentration exhibited a similar pattern with values of 10.1 mg/l in the raw sewage, 10.9 mg/l at sampling point 2 and 12.9 mg/l in the effluent.

The C/N ratio of the raw sewage was 5.17/1, but since the overall treatment process is geared to BOD and/or organic carbon removal, the ratio dropped to 3.32/1, and declined further to 2.72/1 at the pond system effluent. P/N ratios showed similar reductions, namely from 15.7/1 at the raw sewage to 7.8/1 at sampling point 2 and to 6.05/1 at the pond system effluent. It should be noted that the primary and secondary treatment process removed mainly carbon and thereby changed the nutrient composition at the pond influent (sampling point 2) to less favorable ratios of carbon to nutrients than those in the raw sewage. As previously indicated, the approximate range of C/N ratios for algal growth is approximately 4.0 to 20.0 and the range for C/P, approximately 20.0 to 500.0; the above-given ratios for the raw sewage are already low in carbon content, and as previously indicated, is further reduced by the treatment process.

Considering the low C/N and C/P ratios, at the pond influent (after treatment at sampling point 2), a carbon deficiency may be expected in the pond system.

Considering the overall carbon supply in a stabilization pond , it should be kept in mind that since algae cannot directly use the complex organic material present in sewage as a source of carbon or other nutrients, the material must first be broken down by bacteria to forms available to the algae. However, in so doing, the bacteria use a part of the incoming carbon and assorted nutrients for their growth and metabolism, the size of the amount being in proportion to the size of the bacterial population and the availability of carbon. Hence, only the carbon (and other metabolic end-products including CO_2) is available to the algae. In other words, bacteria have first access to the carbon in organic materials in sewage, and algae only have access to the residue of organic carbon. Bacteria and algae have equal access to the inorganic carbon in the pond liquid.

The light-box studies indicated that there are at least two limiting factors for algal growth in the pond system--light and carbon, i.e., additions of light or additions of carbon both brought increased growth.

That light was limiting is not surprising when the 3.5 foot depth (107.0 cm) in the high-rate pond, and the 5.5-foot depth (168.0 cm) of the polishing pond is compared to a light penetration of 50.0 to 55.0 cm as found by secchi disk readings. In other words, only the upper layers of the high-rate and polishing ponds are properly exposed to light.

That carbon was also potentially limited is based on the low nutrient ratios at sampling points 2, 3, 4, and 5, and on the results of the light-box studies, a deficiency in carbon for algal growth seems to be the second cause for the ineffective nutrient removal in the Concord pond system.

Anaerobic Pond. Data presented in Table XIV indicate that the total carbon concentration perhaps increased slightly from 85.0 mg/l to 88.0 mg/l (between sampling points 2 and 3); total nitrogen concentrations also apparently increased slightly from 25.6 mg/l to 28.6 mg/l; and those for phosphate, from 10.9 mg/l to 12.1 mg/l. Two possible reasons for these slight increases in nutrient concentrations have already been mentioned: 1) It seems that a portion of the nutrients within the suspended matter at sampling point 2 escaped chemical analysis, and 2) the change from aerobic conditions in the trickling filter to anaerobic conditions (whereby nutrients are released) in the anaerobic pond. In view of the short detention periods involved, evaporative concentration in the ponds probably does not account for the slight increases found.

High-Rate Pond. Like the anaerobic pond, the high-rate pond removed residual BOD, but showed little evidence of removing nutrients. Here again, several factors must be involved. Two reasons for lack of nutrient removal already indicated in the section on Light-Box Studies are light and carbon deficiencies. An additional factor could be the low pumping rates applied during the study period. By shutting off two of the four available pumps, the pumping rate was reduced below the designed pumping rate, and the velocity was only 0.28 feet per second instead of 0.50 feet per second. This permitted algae and other settleable solids to settle downwards and remain more concentrated near the pond bottom while effluent from the pond was drawn from the surface. Evaporative concentration in the pond must have occurred, but should have been small because of the short detention period involved.

Polishing Pond. The West pond was originally designed to be an algal settling pond, but with a reduction in area due to flood control construction, its design was changed to that of a deep high-rate pond. This was accomplished by deepening the pond from 3 feet to 5.5 feet and installing flow channels and mixing pumps. In this pond all four pumps are operated continuously, and, consequently, good mixing instead of good settling is accomplished. As in the previously discussed pond units, BOD removal efficiency exceeds nutrient removal efficiency. The effluent from this pond contains a mean value of 39.7 mg/l of suspended solids which is mostly algae and is discharged into Walnut Creek or into the dry creek bed. So long as no quality standards for algae containing effluents are established, the discharge of this effluent will be satisfactory. However, should discharge requirements for algae or AGP (algal growth potential) be established (this is a possibility), the effluent containing substantial quantities of nutrients may not be satisfactory for discharge unless filtration or other forms of algal removal are applied.

To summarize the previous findings, because of land shortage and short detention times (especially in the anaerobic pond) the nutrient removal efficiency was very low, but the BOD (organic carbon) removal was satisfactory. If more land could be made available, and the facultative-anaerobic pond enlarged, detention time could be increased to an acceptable 3.2-day period for the high-rate pond.

Elimination of the anaerobic unit would make possible enlargement of the high-rate pond and would probably be advantageous because the trickling filter would then be followed by another aerobic unit without too much change in the microbial population. In other words, it is believed that the evidence shows that the anaerobic pond is misplaced within the system and its removal and replacement by an additional area of high-rate pond would be beneficial.

STUDIES OF THE SAINT HELENA STABILIZATION POND SYSTEM

Introduction

Saint Helena's modern pond system consisting of a series of specially designed ponds was constructed in 1966-67, and was put into operation in August of 1967. Although the initial two ponds filled in a few months, about one and one-half years were required to fill the entire five ponds which constitute the system to overflowing. Consequently, the first effluent was not discharged from the system until February 1969. The receiving body of water for the discharge from the system is the Napa River. The new pond system replaced an older one consisting of four small, shallow ponds operated in series. Because of excessive algal growth and poor sludge digestion on the pond bottom of these shallow ponds, strong odors were emitted during the wine-making season when wine-making waste with low pH levels reached the ponds. The new pond systen was constructed in the hope of eliminating this odor problem and of recharging substantial quantities of water into the ground water. A schematic diagram showing the "layout" of the pond system is shown in Figure 32.

The design of the new Saint Helena pond system incorporates many so-called "natural" treatment processes. The first is anaerobic decomposition in the anaerobic pond. The anaerobic phase is followed by secondary treatment involving photosynthetic oxygenation through algal activity and subsequent oxidation by bacteria present in the partially aerobic bottom sludge in the high-rate pond which receives the discharge from the anaerobic pond. Settling of algae is accomplished in the third pond unit, and final polishing in the last two ponds. A characteristic of the two end ponds is that the environment is conducive to the growth

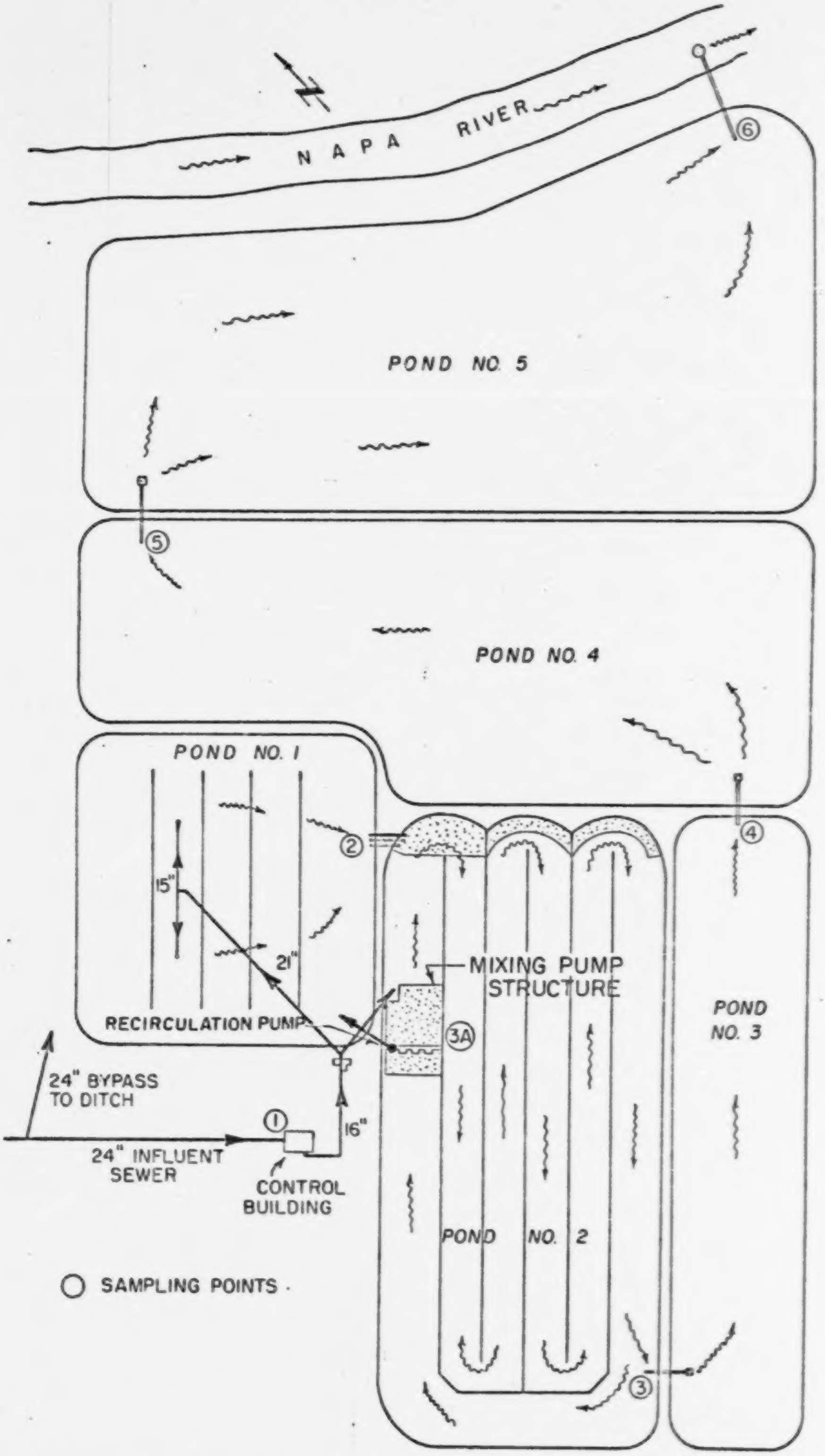
N A P A RIVER
⑥
POND NO. 5
⑤
POND NO. 4
POND NO. 1
④
②
15"
21"
MIXING PUMP STRUCTURE
POND NO. 3
RECIRCULATION PUMP
3A
24" BYPASS TO DITCH
①
16"
24" INFLUENT SEWER
CONTROL BUILDING
POND NO. 2
○ SAMPLING POINTS
③

FIGURE 32-ST. HELENA STABILIZATION POND SYSTEM

of small crustacea such as daphnia which graze on the algae and thereby leave a clear but nutrient-containing effluent.

Description of Pond System

As indicated in Figure 32, the Saint Helena pond system consists of an anaerobic pond (first pond unit), a high-rate pond (second pond unit), an algal settling pond (third pond unit), and two polishing and recharge ponds in series making up a fourth pond unit. The dimensions, capacities, and detention times of the ponds are given in Table XIX.

The detention times indicated in Table XIX were calculated on the basis of an average flow-through of 0.418 MGD. This number is a result of flow measurements made during the 12-month period from April 1969 to March 1970. The flow record is summarized in Table XX. Due to evaporation and percolation, true detention times are substantially longer than the theoretical times based solely on pond volume and flow.

Baffles were installed on the bottom of the 10-foot deep anaerobic pond to aid in distributing the sludge evenly and preventing the bottom portion of the pond from mixing due to overturn. It also should be noted that the "anaerobic" pond is only partly anaerobic, i.e., while the bottom portion is anaerobic, its surface layer is aerobic due to a relatively high concentration of algae. It thus actually functions as a facultative pond.

The high-rate pond is divided into six 50 to 58-feet wide interconnected channels and is equipped with a recirculation structure. The recirculation structure is fitted with three low-head pumps rated at 11,300 gallons per minute (GPM) each. Only one of the three pumps is kept in operation continuously. The average flow velocity through the pond channels with one pump is only 0.16 feet per second or 9.3 feet

TABLE XIX

Capacities and Detention Times of the Saint Helena Ponds

Pond	Area (acres)	Depth (feet)	Volume (ac-feet)	Detention Time* (days)
Anaerobic	2.2	10	22.0	17.1
High-Rate	5.0	3	15.0	11.7
Algae Settling	2.1	8	16.8	13.1
Polishing I	4.3	8	34.4	26.8
Polishing II	5.9	9	53.1	41.3
Total	19.5		141.3	110.0

*Nominal times based on pond volume and influent volume

TABLE XX

Sewage Flows and Rainfall Data

Month	Sewage Flow MGD	Rainfall Inches
April 1969	0.32	2.34
May "	0.29	0.08
June "	0.23	0.11
July "	0.26	--
Aug "	0.27	--
Sep "	0.27	--
Oct "	0.27	2.44
Nov "	0.27	1.64
Dec 1969	0.59	13.58
Jan 1970	1.06	18.43
Feb "	0.69	4.01
Mar "	0.49	1.98

Mean 0.418

Total 44.61 inches
or 3.42 feet

Standard Deviation 0.251

Coefficient of Variation 60%

per minute, a velocity which is barely capable of overturning the liquid.

The third pond unit is a long narrow channel-like pond, 8.0 feet deep where the velocity is very low (theoretical average is 0.04 feet per minute). A portion of the algae settle out of suspension in this pond. As stated in the opening paragraph, the final two ponds (unit four) are for polishing and final disposal of the already well-treated sewage.

Because of percolation and evaporation losses, there is very little effluent to discharge from the pond system. For example, during the 12-month study period, only 10.9 MGD were discharged, whereas the input was 150.4 MGD. Thus, the overflow output was only 7.2% of the input. Outflow occurs only during the rainy winter months when the water level in the receiving Napa River is high. In summer, when the water level in the Napa River is low, all of the treated sewage is retained within the pond system. From June until late November, the last pond (polishing pond II) is practically dry and only four of the five ponds are in operation.

Percolation losses in the system were not measured, but they were calculated by applying the following data and assumptions:

1) Flow:

Influent = 150.4 MGD[1] x 0.326 = 465 AFY[2]

Effluent = 10.9 MGY x 0.326 = 34 AFY

Remaining in pond system 431 AFY

[1] MGY = million gallons per year
[2] AFY = acre-feet per year

2) Evaporation:

Yearly evaporation	7.66 feet
Yearly rainfall	3.42 feet
Yearly net evaporation	4.24 feet

3) Areas:

Considering that the last pond is dry during one-half of the year, the average area for evaporation and percolation was 19.5 - 5.9/2 = 16.55 acres. Therefore the yearly evaporation loss is approximately 4.24 x 16.55 = 70.0 AFY.

4) Percolation:

Yearly volume for loss by percolation is that remaining in the pond system less evaporation, i.e., 431 - 70 = 361 acre-feet.

$\frac{361 \text{ acre-feet}}{16.55 \text{ acres}}$ = 21.8 feet per year or 0.06 feet per day (0.72 inches per day, or 18.0 mm per day). This is a relatively high average percolation rate.

The above calculations apply to the combined ponds and do not give any indication of differences between ponds with regard to percolation rates.

For the reason that no data on differences in percolation rates are available, and for reasons of checking the actual performance data against the original design data (see Table XXXV), no corrections for detention times were made.

Sewage Flow and Sewage Characteristics. Sewage flows for the 12-month period from April 1969 to March 1970, together with amounts of rainfall are given in Table XX. (Rainfall and related infiltration in the collection system leads to an increase in volume of sewage flow). Mean values for the more important indicators of the domestic raw sewage characteristics are BOD - 142.5 mg/1; COD - 307.0 mg/1; total nitrogen - 31.7 mg/1; phosphate - 11.8 mg/1; and alkalinity - 158.2 mg/1. Detailed listings of the constituents of the sewage during the period of the study are given under the heading Sampling Point 1 in the tables and are presented later in this report (Appendix C). The levels of the values indicate that the Saint Helena sewage is a domestic sewage of normal composition at least during the times when winery and other fruit processing wastes are not being discharged into the sewers.

Study Procedures

The study program was divided into three portions: First - available data on pond performance over a yearly period (from March 1969 to February 1970) have been collected and summarized. Second - an intensive sampling program called the spring sampling program was carried out. Most of the data reported in this section were obtained in this spring sampling program. Third - additional samples were collected in July and August 1970 comrpising the summer sampling program.

The spring sampling program was carried out over a six-week period, starting on March 16, 1970 and ending on April 29, 1970. The sampling period included six actual sampling days on which all the required samples were collected. This sampling program was based on the six sampling points shown in Figure 32. Sampling Point 1 is the pump station from which the incoming sewage is pumped into the anaerobic pond. Sampling Point 2 is at the outlet structure of the anaerobic pond; sampling point 3, at the outlet structure of the high-rate pond; sampling point 4, at the outlet structure of the settling pond; sampling point 5, at the outlet structure of polishing pond I; and sampling point 6 near the outlet structure of polishing pond II. Inasmuch as the last-named outlet structure does not extend into polishing pond II, but is directed toward the Napa River, the samples at sampling point 6 were collected near the pond shore line. This fact should be kept in mind when reading this chapter and inspecting the various tables and figures therein.

The shallowness of the pond at the site of the sampling point undoubtedly exerted some influence on the analytical results. In other words, samples collected at this point were less representative of polishing pond II's characteristics than were the other samples characteristic of the ponds from which they were taken. Also, polishing pond II because it normally has no overflow becomes a concentrate because of evaporation.

In general, samples were collected in the morning hours between 9 and 11 AM. Temperature and secci disk readings were made at the pond site. All other analytical determinations, including pH readings, were made in the Sanitary Engineering Research Laboratory at the Richmond Field Station. In order to ascertain the correctness of the delayed pH readings at the Richmond Laboratory, approximate pH readings (with lithmus paper) were made at the pond site.

Results of Study

General. Quality changes as a function of detention time could be followed very closely in the pond system up to 110 days of detention time. Moreover, the "separateness" of the pond units in the Saint Helena system made it possible to study many ecological features. Thus, bacterial action was emphasized in the anaerobic pond, algal activity was emphasized in the high-rate and settling ponds, and the effects of grazing organisms was emphasized in the two polishing ponds when well-established daphnid populations were present.

Because the emphasis in this study was on nutrient balance, on BOD and COD ratios, and on carbon relationships as criteria of pond performance, the sampling program as well as the interpretation of the results were predominantly oriented toward the collection of data which would support these study objectives.

During the second week of April, unusually cold, windy, and rainly weather swept over the area. This cold weather had a marked effect on the pond performance in general and on the settling pond (sampling point 4) in particular. Characteristics of samples collected on April 15 reflected the weather disturbance. The cold weather also had a pronounced effect on the ecological behavior of the pond system, including the algal-daphnia relationship and on the overall population dynamics. The changing front between the algal and daphnia populations could be observed and followed within the relatively short sampling period.

Yearly and Monthly Fluctuations. Analytical data for the year preceding the study (March 1969 to February 1970) were obtained from members of the Saint Helena laboratory personnel who monitor the pond system. They include temperatures, pH readings, and dissolved oxygen concentrations. In the study described herein, these data were analyzed with respect to the sampling points described in the previous section, and are summarized in Tables C-1 through C-5. ("C" indicates Appendix C). Yearly averages taken from these tables are plotted in Figure 33. As shown in the figure, dissolved oxygen concentrations increased progressively through the pond system, starting at a mean concentration of 3.5 mg/1 (37.2% saturation) at sampling point 2, and rising to a mean concentration of 8.3 mg/1 (82.0% saturation) at sampling point 6.

Temperatures decreased from a yearly mean of 17.9^{o}C at sampling point 2 to a yearly mean of 14.8^{o}C at sampling point 6. The relatively lower temperature at sampling point 3 may indicate a slight cooling effect due to mixing in the high-rate pond. The somewhat higher temperatures at sampling point 4 indicates warm-up at least of the surface in the small and unmixed settling pond.

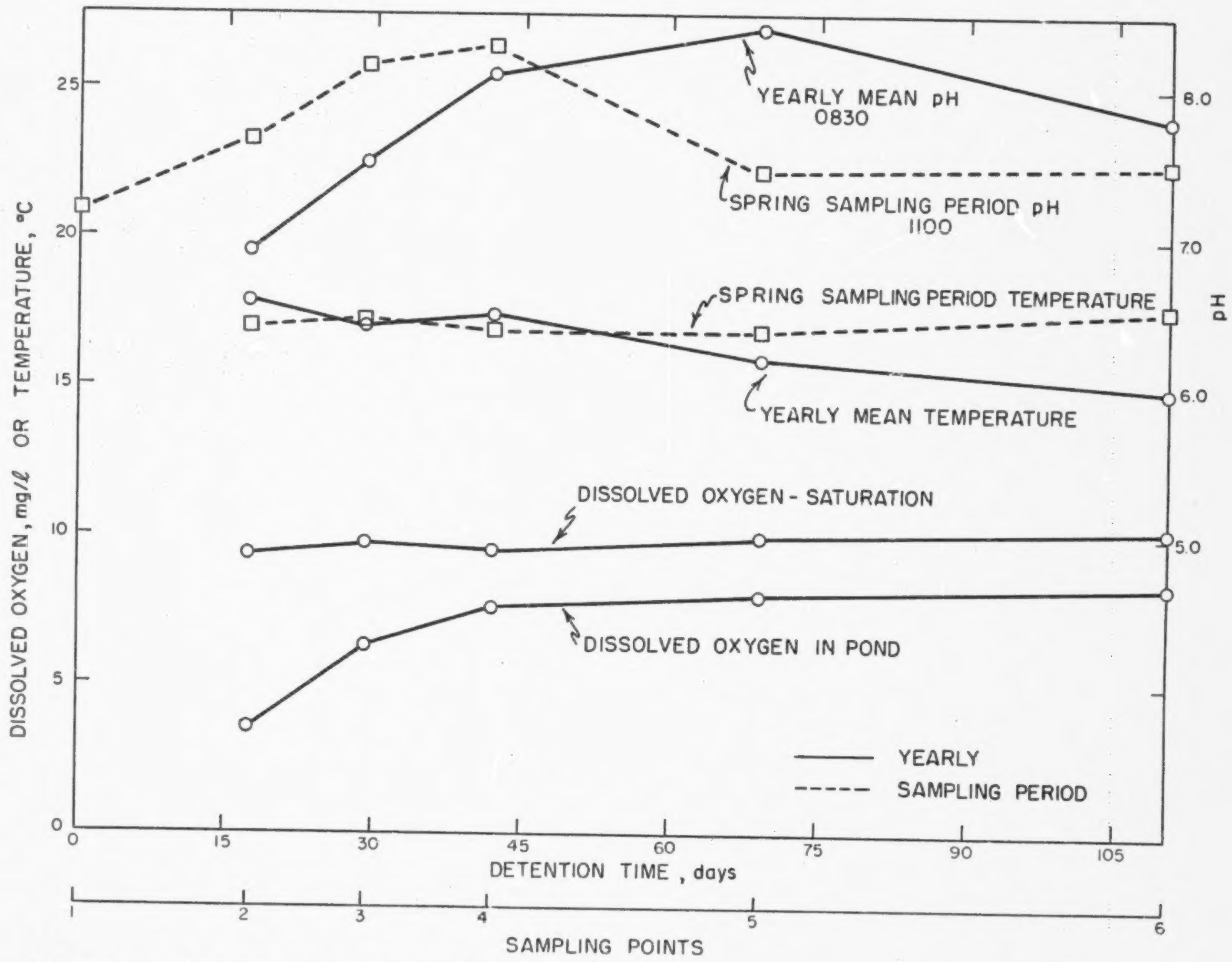

FIGURE 33 - YEARLY MEAN VALUES FOR DISSOLVED OXYGEN, TEMPERATURE, AND pH

The yearly mean pH values differ from those measured in the study period. The reasons for the difference were twofold: 1) The industrial waste (winery and fruit processing wastes) conveyed to the pond system in the winery season (August-October) usually has a low pH. This low pH had a depressing effect on the pH levels in the first two ponds (sampling points 2 and 3). 2) In summertime, due to the higher temperatures prevailing then, the algal front moves into polishing pond I, and possibly overwhelms the daphnia population present during the remaining months. This summer increase in algal growth brings about a rise in pH level in polishing pond I, which according to Harrison (122) had a detrimental effect upon *Potamocyrpis* survival.

The Spring Sampling Program - Physical Characteristics. Temperature and transparency (secchi disk readings) are grouped under this category and hence are described here.

Average temperature values from the samples are summarized in Table C-6 and are shown in Figure 34. The values are irregular and somewhat different from those shown for yearly means. Different sampling points, the adverse weather conditions in April, and the shallow, near-shore samples at sampling point 6 account for the diversity. These differences correspond to those observed for the pH characteristics described in the preceding section.

When considering the differences between the yearly means and sampling period data, the long-range, yearly readings may be assumed to more accurately represent the overall yearly performance of the pond system. However, when considering the pond system's behavior during the major sampling period, the sampling period data for both temperature and pH are the ones of interest.

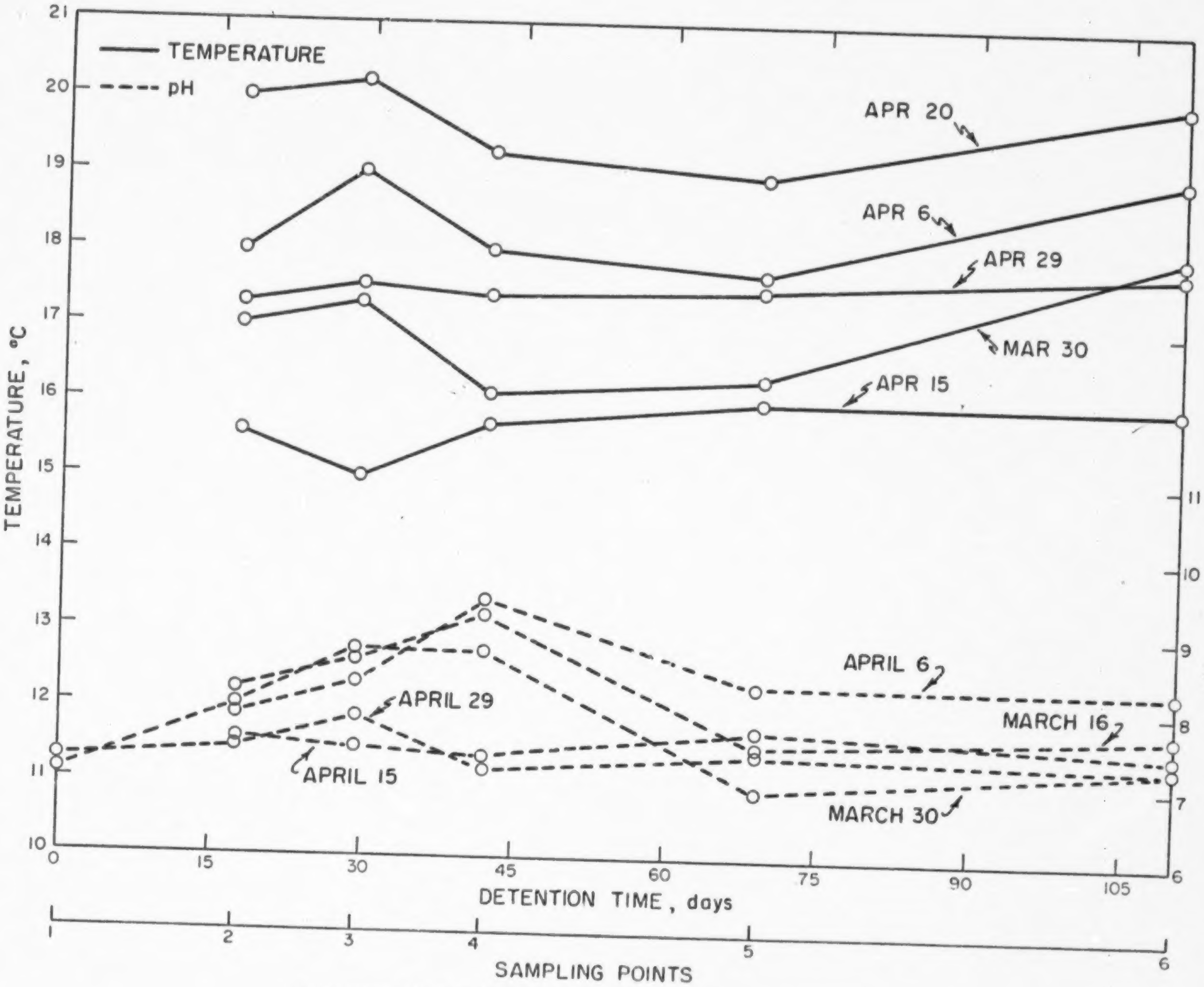

FIGURE 34-TEMPERATURE AND pH LEVELS

Secchi disk readings were made at sampling points 2, 3, 4, and 5. No secchi disk readings were made at sampling point 6 because no suitable structure existed or could be built from which the readings could be made.

The recorded and summarized disk readings over the sampling period are summarized in Table C-7 and shown graphically in Figure 35. In keeping with the numbering of the sampling points, data for point 2 in the tables and figures are those for the anaerobic pond shown as a horizontal line between sampling point 1 and 2 in Figure 35. Sampling point 5 is indicative of polishing pond II shown as a horizontal line between sampling points 5 and 6 in Figure 35.

The lowest mean value for secchi disk readings (23.6 cm) was that for sampling point 3 (high-rate pond). The low mean value indicates 1) a dense algal population and 2) some turbidity due to pumping. This low mean value correlates with a volatile suspended solids concentration (45.7 mg/1) characteristic of that sampling point. The correlation between the secchi disk readings and the volatile suspended solids concentrations is shown in Figure 36.

The readings made at point 4 (settling pond) fluctuated sharply. At the beginning of the sampling period (from March 16 to April 6), warm weather prevailed, and the settling pond had a dense algal population. During the cold spell in the second week of April, however, daphnia invaded the settling pond and the algae disappeared. As a result of the daphnia invasion, and the disappearance of algae, total dissolved solids concentrations decreased sharply and the secchi disk readings increased accordingly.

At sampling point 5 (polishing pond I) the highest secchi disk

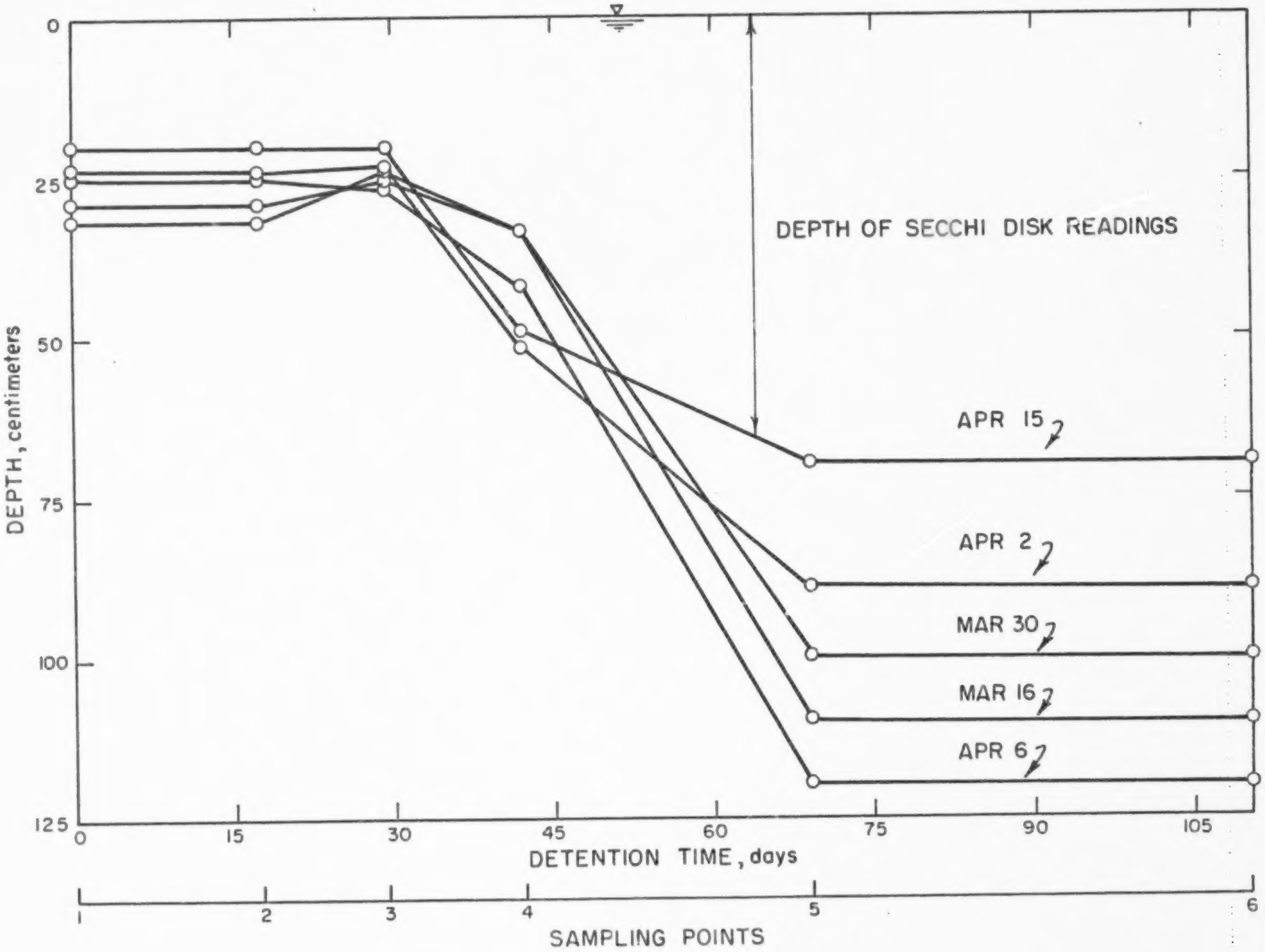

FIGURE 35-SECCHI DISK READINGS

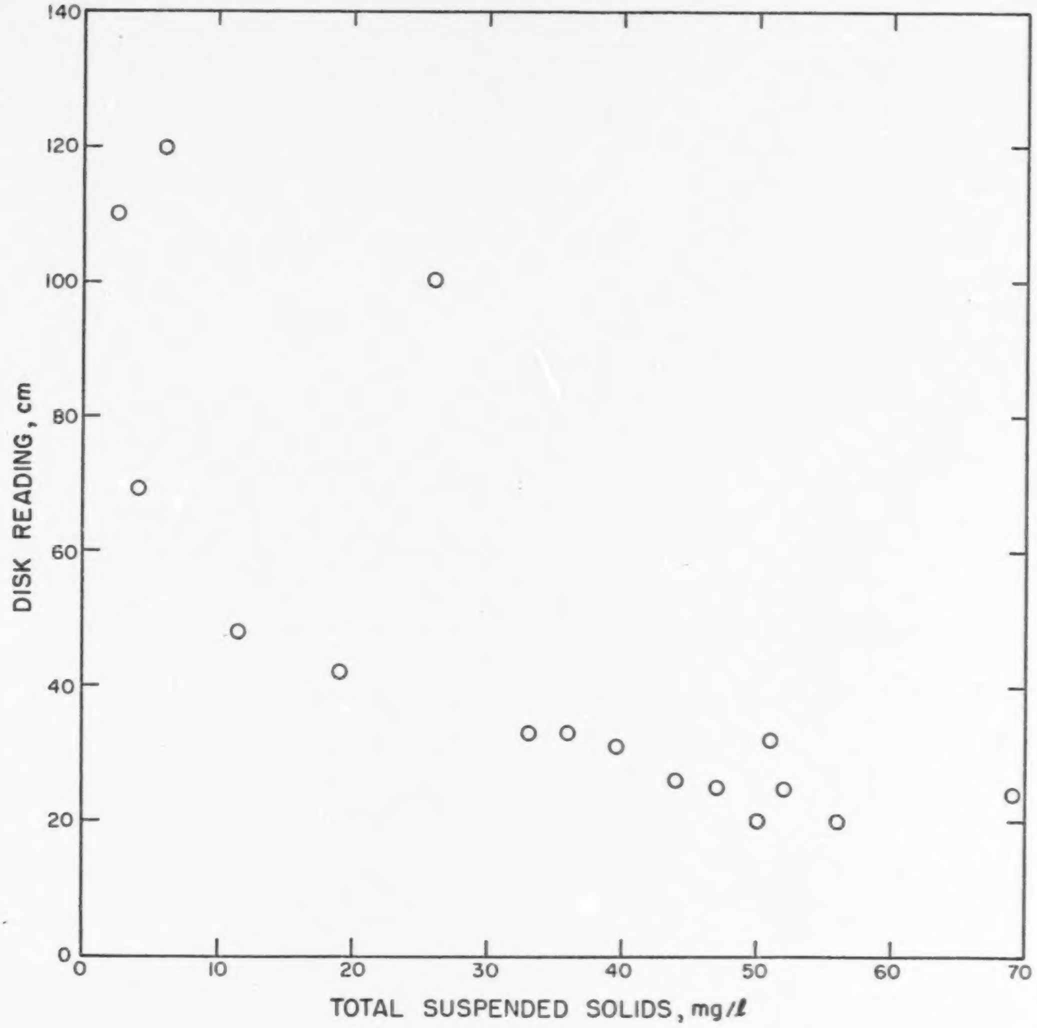

FIGURE 36 – SECCHI DISK READINGS VS SUSPENDED SOLIDS

readings were recorded. The high readings appear to correspond to the low total suspended solids concentrations, and the absence of any visible algal population in the first and second polishing ponds.

By doubling the 23.6 cm secchi disk reading for the high-rate pond to 47.2 cm, one obtains an estimate of the length of total light path had the disk not intercepted the light. Thus, the approximate light penetration in the high-rate pond can be estimated. Since the depth of the high-rate pond is 3 feet (91.5 cm) and the apparent penetration 47.2 cm, light evidently penetrated more than one-half of the pond depth at the time this measurement was made.

Nitrogen and Phosphate Removal: As shown in Figures 37 and 38, the most extensive removal of nitrogen took place in the anaerobic pond, less nitrogen was removed from the high-rate and settling ponds, and only a slight amount disappeared from the two polishing ponds. Ammonia removal followed the general pattern of total nitrogen removal.

Phosphate removal also was greatest in the anaerobic pond, less in the high-rate pond and settling ponds, and almost negligible in the two polishing ponds.

Nitrogen and phosphate concentrations for the six sampling points are given in a summarized form (including the data shown in Appendix C) in Table XXI. For reasons of nutrient balance, carbon concentrations and nutrient ratios are also shown.

The data in Table XXI indicate that residuals for total nitrogen and phosphate were relatively high at sampling point 6 (3.11 mg/l total nitrogen, and 4.2 mg/l phosphate) when the 110 days of detention time are taken into consideration. The reason for the relatively high residuals probably can be traced to the presence of the daphnia population. Daphnia "screen-out" the algae from the two polishing ponds

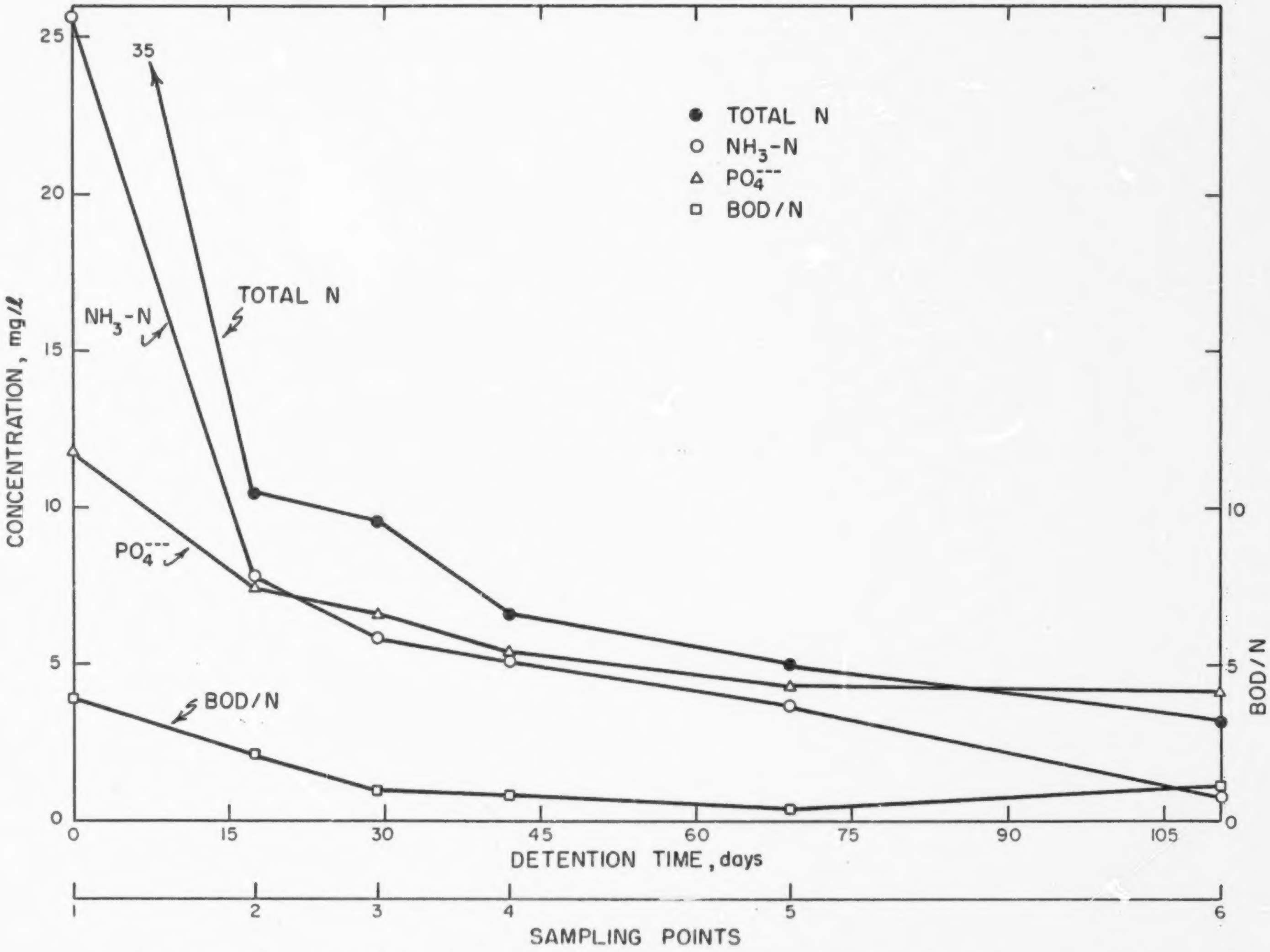

FIGURE 37 - MEAN VALUES FOR NH_3-N, TOTAL-N, PO_4^{---}, AND RATIO OF BOD TO TOTAL-N

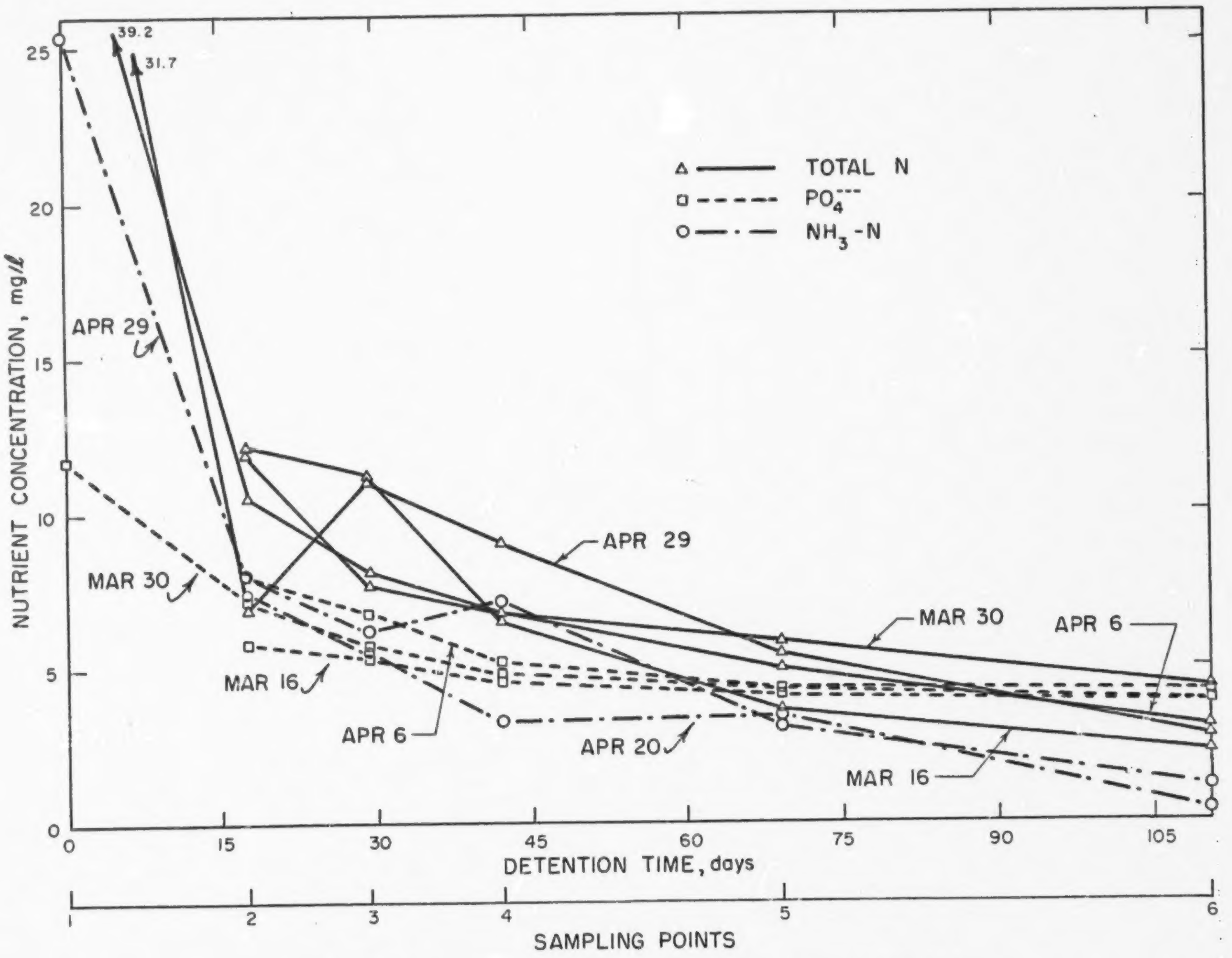

FIGURE 38 - NH_3-N, TOTAL-N, AND PO_4^{---} LEVELS

TABLE XXI

Nutrient Concentrations and Nutrient Ratios

Sampling Point	Nutrient Concentration mg/l			Nutrient Ratios		
	C	N	P	C/N	C/P	N/P
1	131.50	35.40	11.80	3.71	11.14	3.00
2	63.40	10.40	7.52	6.10	8.43	1.38
3	51.00	9.50	6.67	5.37	7.65	1.42
4	42.60	6.60	5.45	6.45	7.82	1.21
5	34.80	5.00	4.40	6.96	7.94	1.14
6	28.00	3.10	4.18	9.03	6.68	0.74

(little chlorophyl was found in these two ponds). The result of the algal elimination by the daphnia is a very low nutrient removal efficiency of the two polishing ponds.

To confirm the assumption of the unfavorable influence of daphnia on nitrogen and phosphate removal, a light-box study was carried out in which polishing pond liquid served as the substrate. Results obtained in the light-box study (described in detail in a later paragraph) demonstrated that the negligible nutrient removal was not the result of an imbalance of nutrients nor the lack of nutrients. It was therefore concluded that the daphnia population was in some way the cause of the deficient nutrient removal.

Depth Profiles of the High-Rate Pond: Depth profiles for the high-rate pond are shown in Figures 39 and 40. The curves in Figure 39 show changes in levels of temperature, pH, and dissolved oxygen with increasing pond depth. The temperature changes are not great, but they do indicate, as one would expect, that a somewhat higher temperature prevails on the pond surface than at the pond bottom. The hydrogen ion concentration expressed as pH remained practically the same throughout the depth profile. Changes were greatest in the dissolved oxygen concentration. It dropped from 4.2 mg/l at the pond surface to 3.0 mg/l at the pond bottom. Nevertheless, this minimum of 3.0 mg/l was more than sufficient to insure aerobic conditions throughout the pond depth.

Figure 40 shows the concentration changes for the three carbon fractions, total nitrogen, phosphate, total and volatile solids, and alkalinity. As previously explained, mixing in the high-rate pond was nominal, inasmuch as the mean velocity was only 0.16 ft. per second. This low velocity apparently is insufficient to prevent some stratification in the high-rate pond. According to the data, stratification was

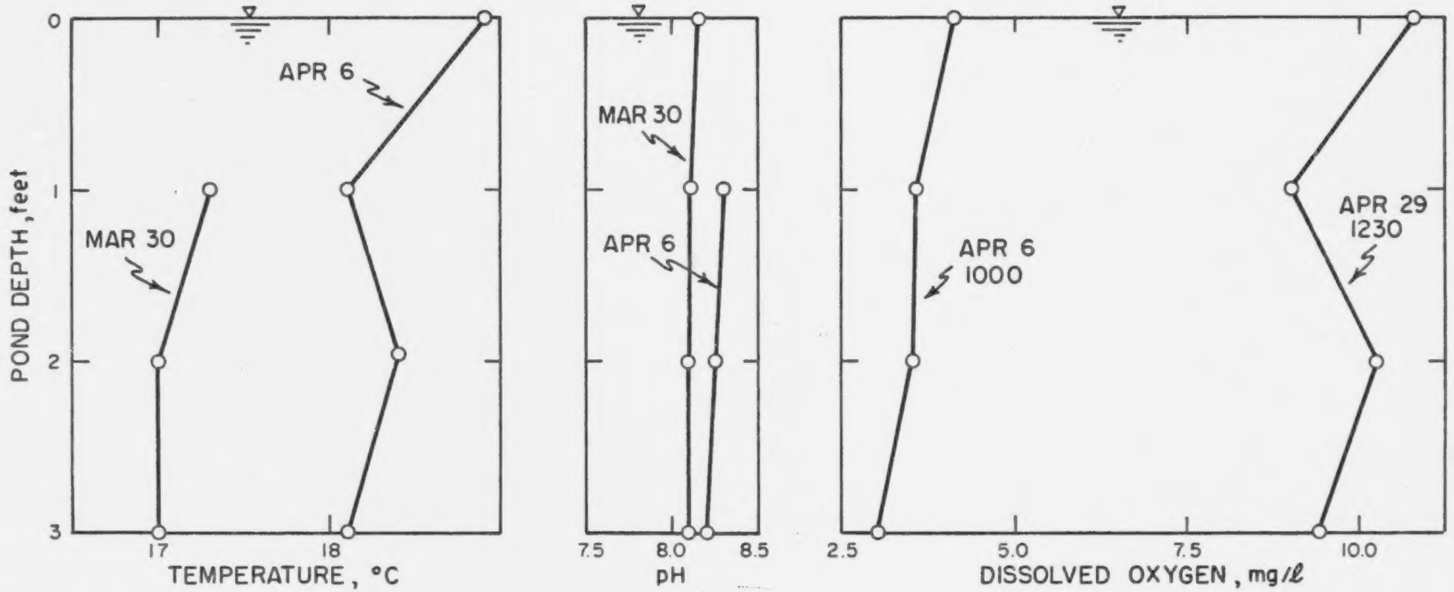

FIGURE 39 - DEPTH PROFILE OF HIGH-RATE POND

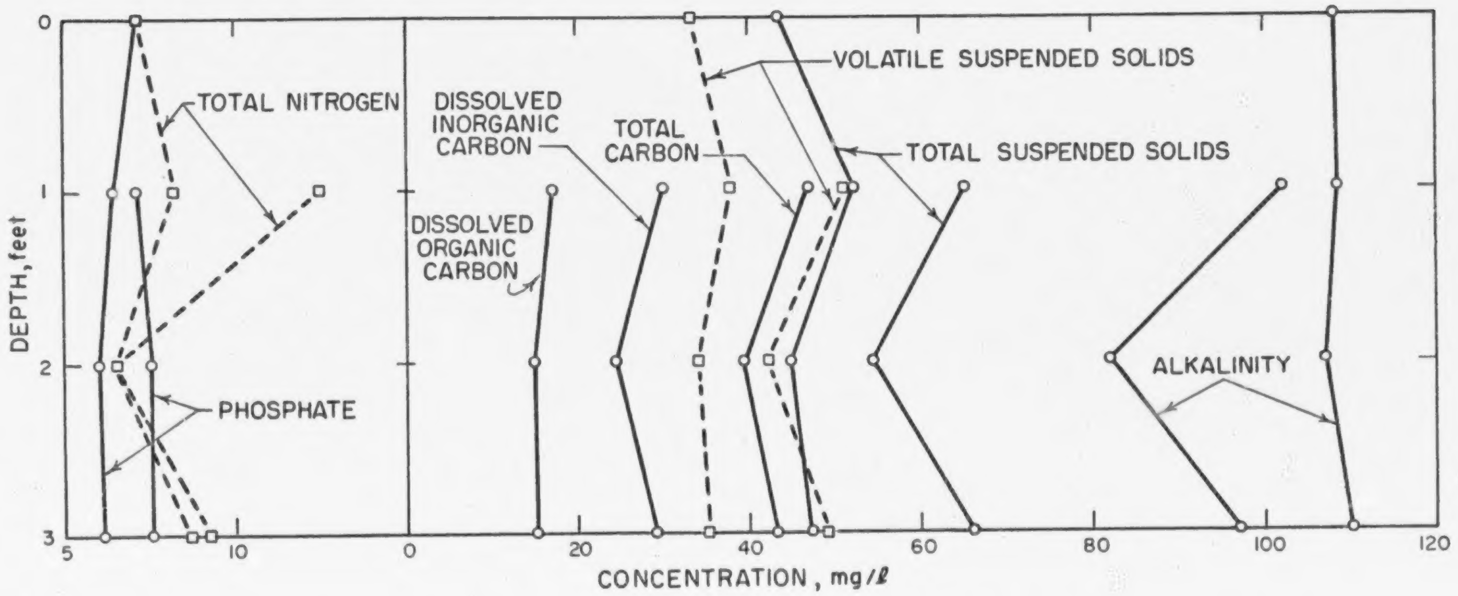

FIGURE 40– DEPTH PROFILE OF HIGH-RATE POND

found about one foot below the pond surface. In this layer, the concentrations of almost all nutrients, as well as suspended solids, were greater than in any other stratum in the pond. The higher concentration of nutrients and suspended solids near the pond bottom can be explained by sedimentation and the existence of a bacterial sludge layer that is actively involved in the breakdown of suspended solids of sewage origin and of debris from algae. The curve for total suspended solids in Figure 40 like the curves for all of the other constituent concentrations is somewhat irregular. It seems to reach a maximum at 1 foot, possibly indicating a concentration of algae at that level.

From the above, it is strongly indicated that the low pumping rate used creates a velocity too low to bring about a complete vertical mixing of the pond contents. However, it seems to have been sufficient to transport dissolved oxygen throughout the depth (cf. Fig. 39), and thereby to maintain an aerobic oxidative condition throughout the liquid profile of the pond.

Figure 41 shows the changes which took place in the BOD, COD, T-C content in the Saint Helena system on each sampling day. The computed mean values of the three parameters from the tables in Appendix C are presented in Figure 42. In the interests of simplicity, in the computations and discussions which follow, only the mean values of all groups of readings will be used.

To obtain a clear picture for the BOD, COD, and T-C reductions, the different reduction rates were computed and are listed in a summarized form in Table XXII. Data in the table include those for total reduction and those for reduction between sampling points. Total reduction refers to the overall reduction which takes place as the sewage or pond liquid

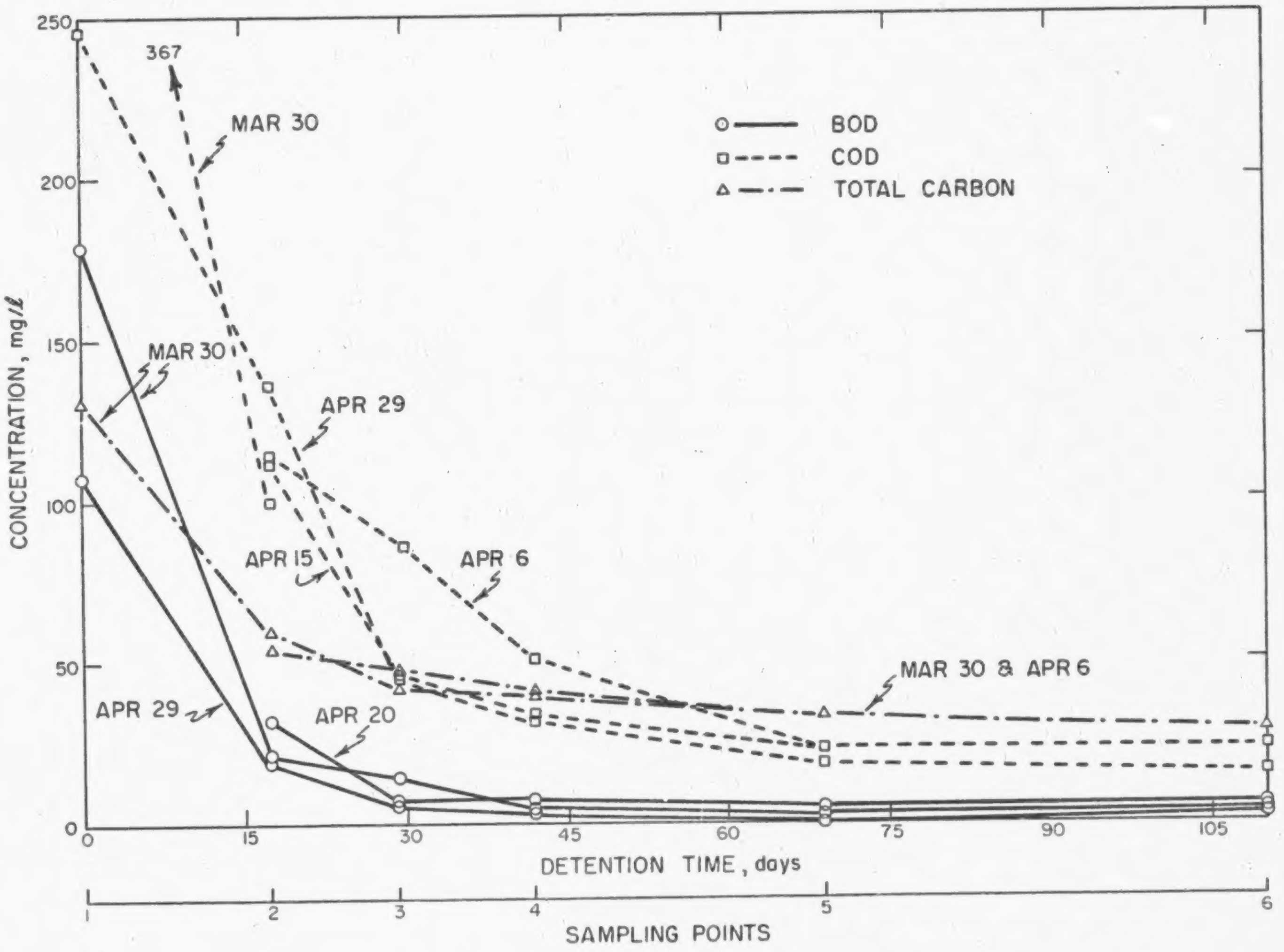

FIGURE 41 - BOD, COD, AND TOTAL CARBON LEVELS

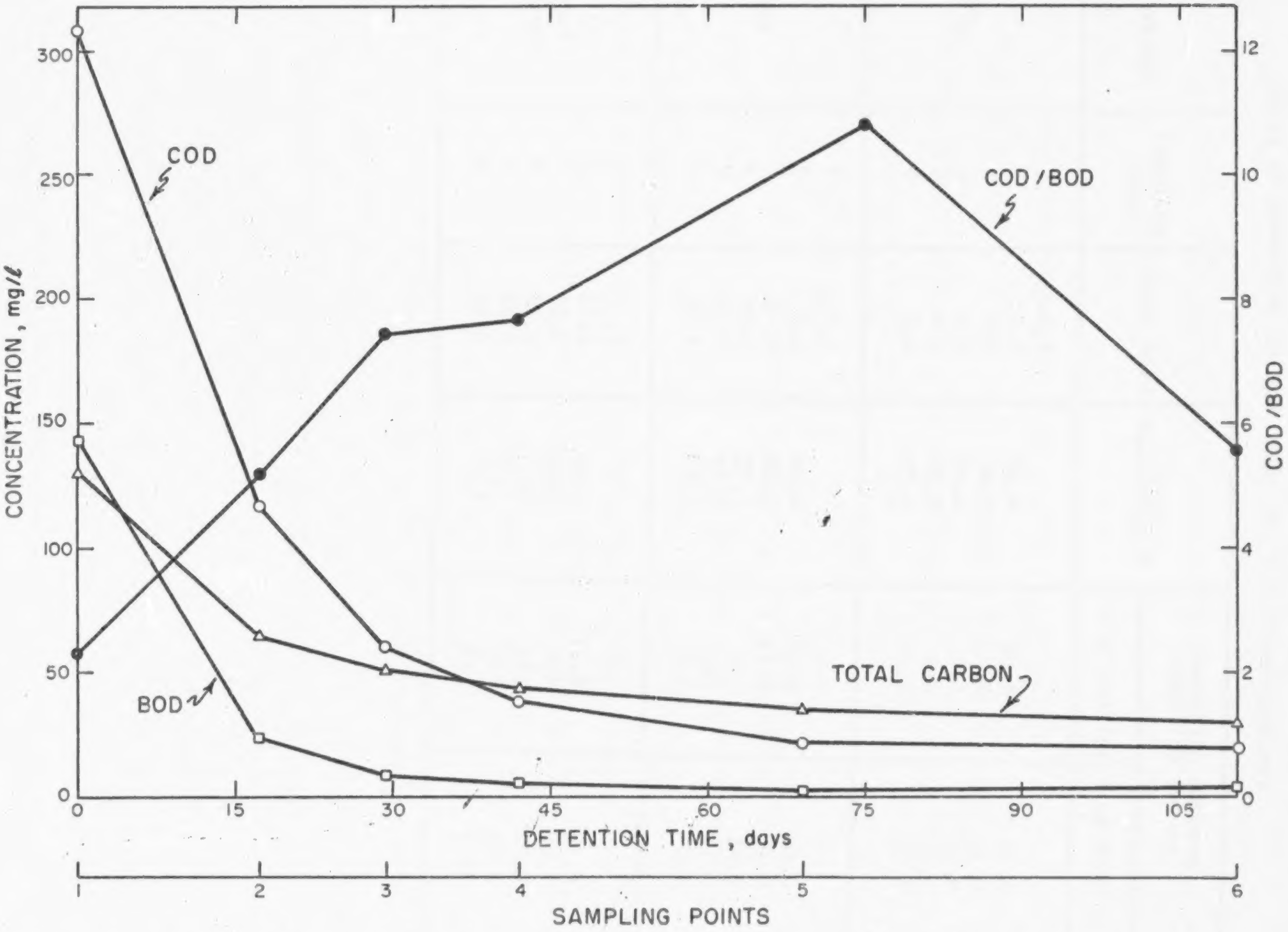

FIGURE 42- MEAN VALUES OF BOD, COD, TOTAL CARBON, AND RATIO OF COD TO BOD

TABLE XXII

Rates of Reduction in BOD, COD, and T-C Concentrations

Parameter	Sampling Point	Conc. mg/l	Total Reduction %	Reduction Between Sampling Points	
				% of Initial	% of Remain.
BOD	1	142.5			
	2	22.2	84.4	84.4	84.4
	3	8.2	94.2	9.8	67.0
	4	5.1	96.4	2.2	37.8
	5	2.1	98.5	2.1	58.7
	6	3.9	97.3	-1.2	-85.5
COD	1	307.0			
	2	115.8	62.4	62.4	62.4
	3	60.9	80.2	17.8	34.6
	4	39.0	87.3	7.1	36.0
	5	22.7	92.5	5.3	41.7
	6	21.6	93.2	0.6	4.7
Total Carbon	1	131.5			
	2	63.5	51.7	51.8	51.8
	3	51.0	61.2	9.5	19.7
	4	42.6	67.6	6.4	16.5
	5	34.8	73.5	5.9	18.3
	6	28.0	78.7	5.1	19.5

advances through the pond system. It is based on measurements taken at each sampling point. Reduction between sampling points means the reduction which takes place within the confines of an individual pond in the system. It is the difference between the concentration (% of initial) of the influent to the pond and the concentration of the effluent from it.

As previously mentioned, data from sampling point 6 should be evaluated on the basis that the fifth pond of the system is actually terminal and that pond 6 only provides evaporative concentration of salts, nutrients and other soluble substances, thus drawing a poorer quality than pond 5.

On the basis of information given in Figure 42 and Table XXII, it can be seen that BOD reduction proceeded at a fast pace with close to 100% reduction at the effluent and with a large 84.5% reduction in the anaerobic unit alone. COD reduction was slower. A reduction of only 62.4% took place in the anaerobic unit, while the reduction for the system on a whole was 93.2%. The most stable, and perhaps the most reliable parameter, proved to be T-C (total carbon). The reduction of T-C was 51.8% in the anaerobic unit, while the total reduction in the system as a whole amounted to 78.2%. Thus, 21.8% of the dissolved organic and inorganic carbon introduced into the system would have been discharged with the effluent if there had been one.

The COD/BOD ratios as given in Table XXIII increased from a 2.15/1 at sampling point 1, to 5.20/1 at sampling point 2, and to 5.54/1 at sampling point 6. The increase in magnitude of the ratios indicates that most of the easily degradable organic material was decomposed, probably in the bottom layers, and oxidized probably in the top layers

TABLE XXIII

COD, BOD and T-C Levels and Ratios

Sampling Point	Levels mg/l			Ratios		
	COD	BOD	T-C	$\frac{COD}{BOD}$	$\frac{BOD}{T\text{-}C}$	$\frac{COD}{T\text{-}C}$
1	307.0	142.5	131.5	2.15	1.08	2.33
2	115.8	22.2	63.4	5.21	0.35	1.83
3	60.9	8.2	51.0	7.43	0.16	1.19
4	39.0	5.1	42.6	7.65	0.12	0.92
5	22.7	2.1	34.8	10.80	0.06	0.65
6	21.6	3.9	28.0	5.54	0.14	0.77

of the anaerobic pond unit. As the sewage and/or the pond liquid progressed through the pond system, a humus-like and increasingly stable organic matter became noticeable. It could have been either a product synthesized in the pond, or simply an evaporation concentrated residue remaining after the degradable material was decomposed. This resistant fraction is not responsive to the BOD determination. However, the existence of the material became evident in the results of a carbon analysis of the dissolved organic fraction.

Carbon Determinations: As noted previously, carbon determinations were made of the liquid and solid portion of the incoming sewage and the pond liquid. With instruments available at the Sanitary Engineering Research Laboratory, the organic and inorganic fraction of the liquid portion (including well-dispersed algae) could be measured. However, with respect to the suspended solids portion of the incoming sewage, only the total carbon concentration could be determined.

The percentages of carbon in the different fractions of the sewage and pond liquid were calculated on the basis of mean values obtained in analyzing the March 30 and April 6 samples. These percentages, together with the actual concentrations, are summarized in Table XXIV and are shown graphically in Figures 43 and 44.

The curves in Figure 43 indicate that while carbon in the suspended solids which is measured as BOD could be regarded as meaningful for readings taken at sampling points 1 to 4 inclusive, measurements at points 5 and 6 contain no measurable suspended solids and measurement of the dissolved organic and inorganic carbon fraction measured by T.O.C. and T-C would therefore be more meaningful in describing the pond liquid characteristics at points 5 and 6.

TABLE XXIV

Percentage Carbon in the Dissolved Organic and Inorganic Portion and in the Suspended Solids of the Influent and Pond Liquid

	Sampling Points											
	1		2		3		4		5		6	
	mg/1	%	mg/1	%	mg/1	%	mg/1	%	mg/1	%	mg/1	%
Liquid - Dissolved Inorganic	43.0	32.7	33.4	52.7	29.5	57.8	27.8	65.1	26.2	7.5	22.5	80.4
Liquid - Dissolved Organic	14.5	11.0	15.6	26.0	15.7	30.8	11.5	26.9	8.5	24.5	5.5	19.6
Liquid - Subtotal	57.5	43.7	49.0	78.7	45.2	88.6	39.3	92.0	34.7	100.0	28.0	100.0
Solid - Subtotal	74.0	56.3	14.4	21.3	5.8	11.4	3.4	8.0	0.0	0.0	0.0	0.0
Total Carbon	131.5	100.0	63.4	100.0	51.0	100.0	42.7	100.0	34.7	100.0	28.0	100.0

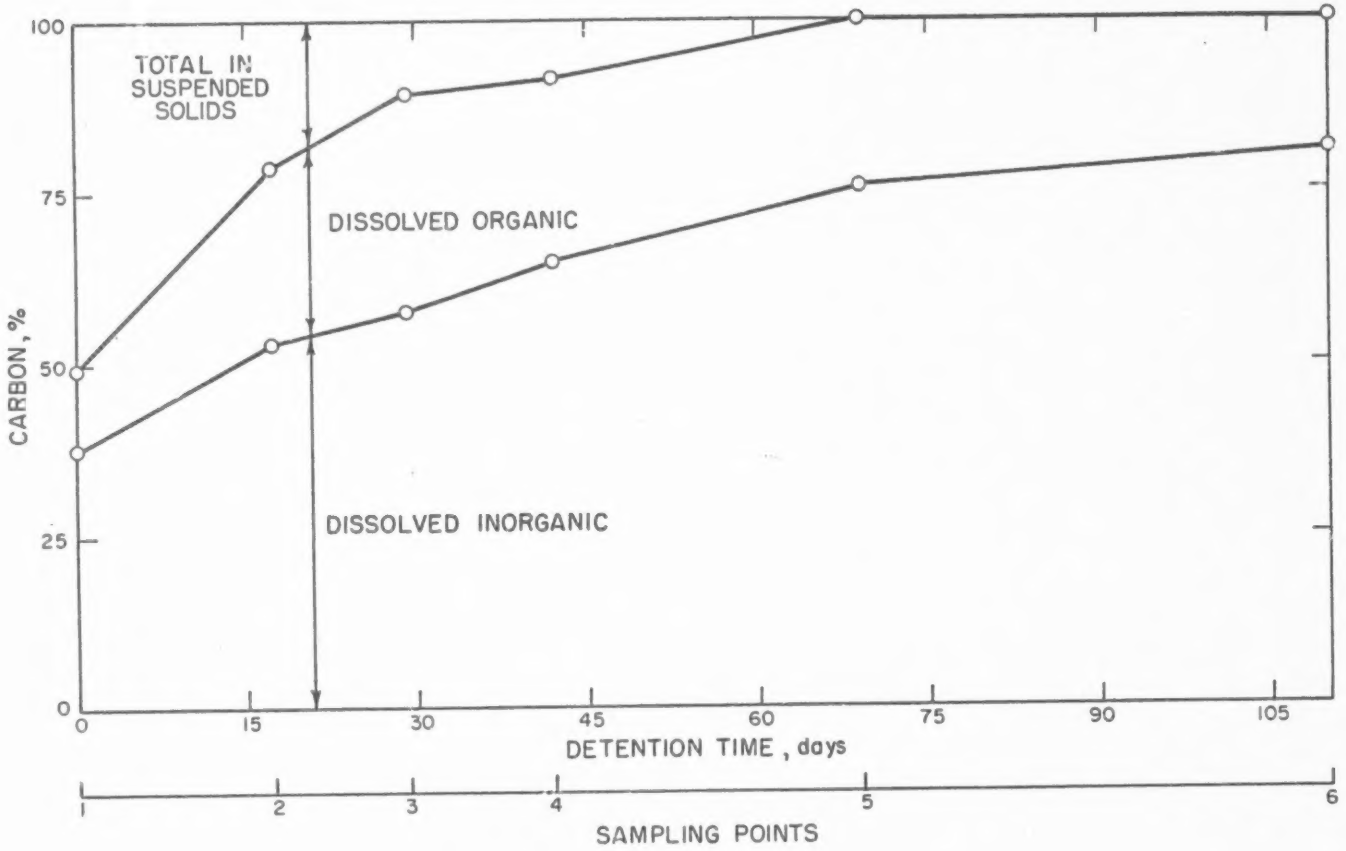

FIGURE 43 - PERCENTAGE CARBON

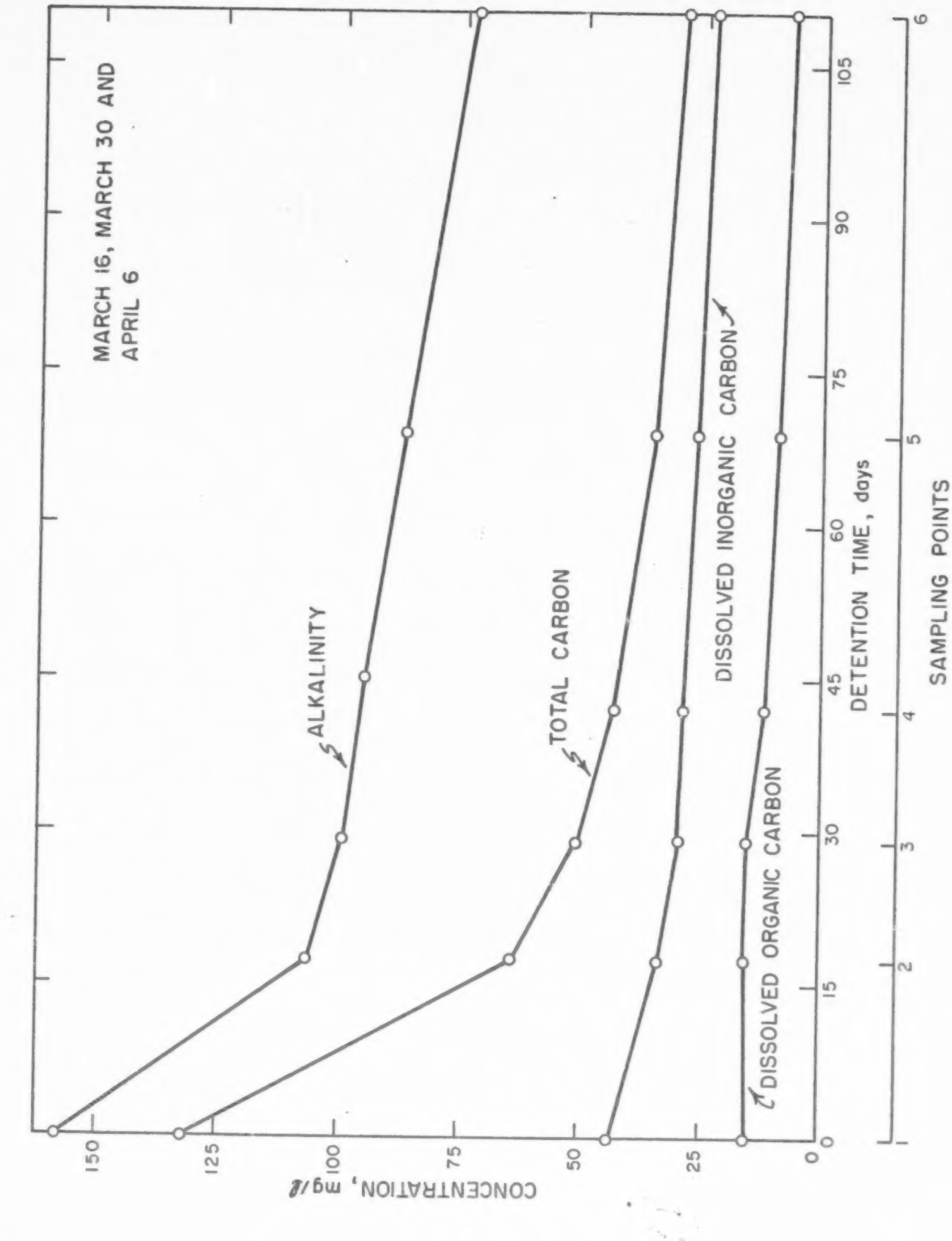

FIGURE 44 - MEAN VALUES OF CARBON AND ALKALINITY

Suspended Solids. Data pertaining to suspended and volatile solids concentration are plotted in Figure 45 and are shown in Tables C-9 and C-10. The sharp decreases in total suspended solid concentration between sampling point 1 and sampling point 2 in the anaerobic pond is to be expected because settling occurs during 17.1 days of detention time. From sampling point 2 to sampling point 3 (in the high-rate pond), a slight increase in total suspended and volatile suspended solids took place. This increase was caused by the intensive algal growth in the high-rate pond as compared with that at the top layers of the anaerobic pond. However, this trend was reversed on test sampling day, April 29, when the concentration of algae in the top layer of the anaerobic pond proved to be higher than that in the high-rate pond.

The greatest decrease in volatile solids concentration (assumed to be algal cells) noted at sampling point 4 is of interest. At this sampling point, the concentrations of volatile suspended solids dropped from 26.9 mg/l on March 16 to 7.2 mg/l on April 15. This decrease was the result of a cold spell, and subsequent appearance of daphnia in the settling pond. The extremely low volatile solids concentrations at sampling points 5 and 6 is believed to be due to that daphnia invasion of the pond.

Light-Box Studies: In order to find out if there was any deficiency or imbalance of nutrients in the pond liquid of the polishing ponds to account for the observed absence of any appreciable algal population in them, light-box studies were undertaken. (Chlorophyll analyses of pond samples gave zero readings). These studies were carried out on samples taken from sampling point 6 on April 6, 1970. The characteristics of the pond liquid at that point and that date are recorded in Table XXV.

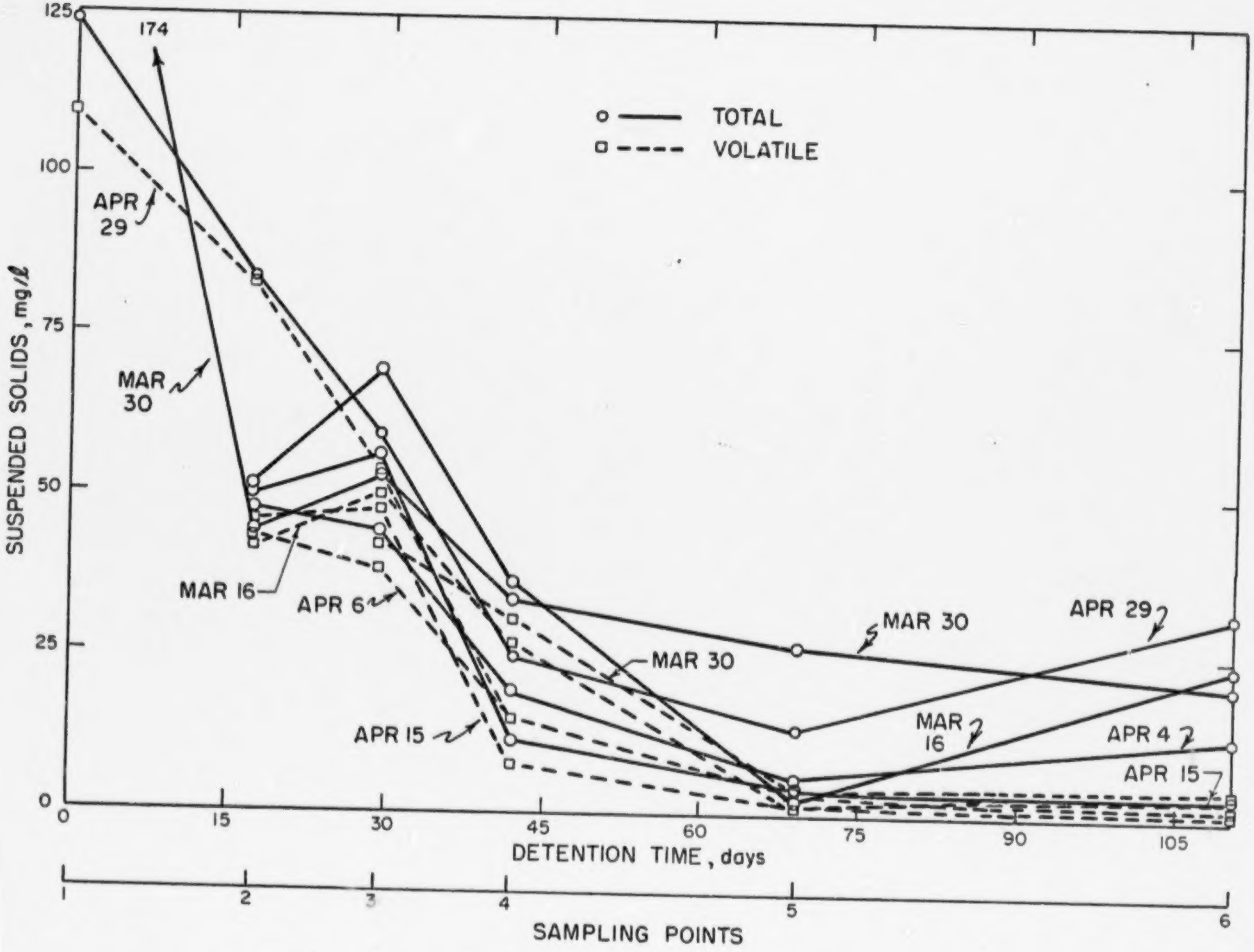

FIGURE 45 - SUSPENDED SOLIDS IN POND LIQUID

TABLE XXV

Characteristics of Pond Liquid at Sampling Point 6 on April 6, 1970

Temperature	19°C
pH	8.25
Total Suspended Solids	12.4 mg/1
Volatile Suspended Solids	4.2 mg/1
Total Nitrogen	3.1 mg/1
Phosphate	3.9 mg/1
Alkalinity	75.2 mg/1
Total Carbon	28.5 mg/1
Chemical Oxygen Deman	27.0 mg/1

TABLE XXVI

Nutrients Added to Remaining Five Flasks

Flask No.	Media	Conc. mg/l	Nutrient Conc. mg/l	C/N Ratios
1	None	--		
2	$NaHCO_3$	25	3.5 as C	10.3
3	$K\ NO_3$	12	1.7 as N	5.9
4	$KH_2\ PO_4$	9	2.0 as P	
5	FE versonal 120	1.74	--	
6	Micronutrients	1.0	See Table C-21	

TABLE XXVII

Chlorophyll Measurements of Flask Cultures in the Light-Box Study
(all values in mg/1)

Media	Natural Light*			Light Box		
	Chlorophyll			Chlorophyll		
	a	b	Total	a	b	Total
Control	1.00	1.07	2.07	1.81	2.14	3.95
$NaHCO_3$	1.16	1.19	2.35	1.78	2.08	3.86
KNO_3	0.90	0.93	1.83	1.53	1.80	3.33
KH_2PO_4	0.88	0.82	1.70	1.71	2.08	3.79
Fe Versonol 120	0.47	0.59	1.06	0.68	0.86	1.54
Micronutrients	0.61	0.78	1.39	1.53	1.73	3.26

*North window

light. Except for the flask containing the buffer, KH_2PO_4, observations of pH levels showed no particular trend in terms of differences in media or exposure to light. The pH of the medium dosed with KH_2PO_4 was consistently lower than that of the other media.

On the basis of the results of the light-box study, it may be concluded that none of the nutrients tested were lacking in the pond, and hence their deficiency could not have been the cause of the very limited algal content characteristic of the polishing ponds. However, the daphnia population was probably responsible for the limiting algal content in the polishing ponds.

Daphnia Population. As previously mentioned, a dense daphnia population was found in the Saint Helena pond system. This daphnia population was exceptionally large when cooler weather prevailed. The daphnia moved like a front from polishing pond I into the settling pond at low temperatures and retreated into polishing pond II when warmer temperatures occurred.

A review of the literature (106) indicated that ammonia in relatively low concentrations is toxic to daphnia (107); and that temperature, dissolved oxygen and food supply may have been the most important factor controlling daphnia population (108).

In order to explore the possibility that ammonia or dissolved oxygen acted as controlling factors of the daphnia population in the Saint Helena ponds, two bioassays were carried out. In the first assay, one-liter beakers were filled with tap water (dissolved oxygen concentration of 9.4 mg/1) and by adding ammonium nitrate, the ammonia concentrations in the beakers were raised from 5 to 100 mg/1. In addition, one beaker was filled with primary treated sewage, and one beaker with secondary treated sewage. The results of the first test run as summarized in Table XXVIII indicate that only ammonia concentrations higher than 40 mg/l had any recordable effect on the daphnia population. One hundred percent mortality (LD 100) occurred only in the beaker with a 100 mg/l ammonia concentration. The shorter time (9 hrs) for a 50% mortality (LD 50) was found in the beaker filled with primary sewage. The ammonia concentration in this beaker was not analyzed, but the measured dissolved oxygen concentration was zero.

Because of this zero reading for the dissolved oxygen concentration, and the obvious possibility that low dissolved oxygen concentrations would limit daphnia growth, a second test was started with variable dissolved oxygen concentrations. The dissolved oxygen concentrations in this second test run ranged from 0.1 mg/l to 9.4 mg/l. Four daphnia organisms were placed in closed BOD bottles and their mortality was recorded.

The results of this second test are shown in Table XXIX and they indicate that reduced dissolved oxygen concentration was probably the significant factor in reducing the daphnia population. Although these sample results can hardly be regarded as conclusive, and although individual differences arise, the results obtained do indicate that 3.0 mg/l dissolved oxygen concentration seems critical for the survival of those daphnia organisms tested.

As mentioned above, dissolved oxygen is believed to be a significant controlling factor for daphnia. This finding is somewhat at variance with those of Leendolf (108) who states that, "Temperature appears to be the most important single physical factor controlling the Cladorcera population." It is, however, well known that the saturation

TABLE XXIX

Influence of Dissolved Oxygen Concentrations on the Survival of Daphnia

No.	Dissolved Oxygen in mg/l	Dead Organisms hours and minutes				Dead Organisms After 25.5 hr
		1	2	3	4	
1	0.10	1 hr 20'	1 hr 50'	2 hr 30'	4 hr 30'	4
2	0.92	1 hr 30'	23 hr	--	--	2
3	1.95	20 hr	--	--	--	1
4	3.04	6 hr 30'	23 hr	25 hr 30'	--	3
5	4.07	--	--	--	--	0
6	6.18	--	--	--	--	0
7	6.90	--	--	--	--	0
8	9.38	--	--	--	--	0

values for dissolved oxygen in water rises as temperatures decline, hence the two findings may not be irreconcilable. The daphnia invade the settling pond in cool weather and retreat into polishing pond II in warm weather and almost disappeared in the summer (August sampling). This phenomenon can be explained by the dissolved oxygen-temperature relationship. Daphnia, as an organism which depends on oxidative metabolism needs a certain amount of dissolved oxygen levels for survival (approximately 3.0 mg/l as found in this study), and dissolved oxygen concentrations may, therefore, be a major controlling factor in regards to the location of the daphnia in a pond system. From the summer sampling program, and from observations made by the operator of the Saint Helena pond system, the daphnia movement may be described as follows. In winter, when higher dissolved oxygen concentrations prevail, daphnia populations are found in the settling pond, that means closer to the primary pond units (anaerobic and high-rate pond), and in summer, when dissolved oxygen concentrations are lower, daphnia retreat toward the last pond unit (polishing pond I is the last unit in summer) or disappear completely. In addition to the seasonal changes in dissolved oxygen concentrations, the diurnal changes which occur must also be considered. This means that the low dissolved oxygen concentrations at night seem to determine the actual daphnia front. Harrison (122) has also presented evidence that pH is influential in controlling _Potamocypris_ populations, the relationship being that _Potamocypris_ are unable to survive pH levels above 12.

Treatment Efficiencies. The treatment efficiency of the Saint Helena pond system was evaluated by three parameters: 1) BOD removal, 2) nutrient removal; and 3) light conversion efficiency.

1) BOD Removal: The BOD rate constant K is used herein for evaluating the efficiency of the treatment process.

The conventional BOD equation (4-1) was used without a temperature correction (temperature differences between the pond units are negligible in making the following comparisons). By using the percentages of BOD reduction given in Table XXII, and the detention times as given in Table XIX, the rate constant K may be calculated for each of the units as was done for the Concord unit (cf. page 134) and are given in Table XXX.

Because of the long detention times, the rate constants are relatively small; however, they indicate the magnitude of differences of BOD removal rates for the different pond units.

Nutrient Removal. Rate constants are not being used for nutrient removal and the effectiveness of removal are evaluated as "unit reductions" on both an acre and acre-foot basis. The unit reductions for nitrogen and phosphate were calculated and are summarized in Table XXXI and Table XXXII. The BOD loadings and unit reductions are summarized in Table XXXIII.

The magnitude of efficiency differences between the pond units based on lb/acre/day values are surprising, and it can be seen that the area of the individual pond units greatly influences nutrient removal efficiency.

Light Conversion Efficiency. Light conversion efficiency was evaluated by using Oswald's formula as described in the Concord studies.

The values for ΔC_c, d, and θ were taken from tables C-7, C-10, and XIX. For the anaerobic pond, the mean value for ΔC_c is 53.4 mg/l, the mean values of d (twice the secchi disk readings) is 50.8 cm and the

Table XXX

Rate Constants for Saint Helena Pond Units

Pond Unit	Rate Constant K in days^{-1}
Anaerobic	0.047
High-Rate	0.041
Settling	0.016
Polishing I	0.014
Polishing II	No BOD reduction

TABLE XXXI

Nitrogen Loadings and Reduction Efficiencies

Pond Unit	Area	Influent Concentration mg/1	Loading	Reduction	Reduction Efficiency	
	Acres		lb/acre/day	%	lb/acre/day	lb/acre foot/day
Anaerobic	2.2	35.4	56.2	67.5	38.0	3.80
High-Rate	5.0	11.5	8.0	17.4	1.4	0.47
Settling	2.1	9.5	15.8	30.5	4.8	0.60
Polishing I	4.3	6.6	5.4	24.2	1.3	0.16
Polishing II	5.9	5.0	3.0	38.0	1.1	0.13
Overall	19.5		6.4	91.6	5.7	0.78

TABLE XXXII

Phosphate Loadings and Reduction Efficiencies

Pond Unit	Area Acres	Influent Concentration (mg/1)	Loading lb/acre/day	Reduction %	Reduction Efficiency lb/acre/day	Reduction Efficiency lb/acre-foot/day
Anaerobic	2.2	11.80	18.80	36.3	6.82	0.58
High-Rate	5.0	7.52	5.25	11.3	0.59	0.20
Settling	2.1	6.67	11.10	18.3	2.03	0.25
Polishing I	4.3	5.45	4.45	19.3	0.86	0.11
Polishing II	5.9	4.40	2.62	5.0	0.13	0.01
Overall	19.5		2.11	64.3	1.37	0.19

TABLE XXXII

BOD Loadings and Reduction Efficiencies

Pond Unit	Area Acres	Influent Concentration mg/1	Loading 1b/acre/day	Reduction %	Reduction Efficiency	
					1b/acre/day	1b/acre-foot/day
Anaerobic	2.2	142.5	226.0	84.4	190.0	19.00
High-Rate	5.0	22.2	15.5	67.0	9.8	3.25
Settling	2.1	8.2	13.7	37.8	5.2	0.60
Polishing I	4.3	5.1	4.2	58.7	2.4	0.30
Polishing II	5.9	2.1	1.25	60.0	1.8	0.08
Overall	19.5		25.5	97.2	24.8	3.42

detention time θ 17.1 days. By introducing these values in the formula (4-2), we may calculate for the anaerobic pond:

$$6 \times 53.4 = F \times 190 \times \frac{10}{50.8} \times 17.1 \quad \frac{6 \times 53.4 \times 50.8}{190 \times 10 \times 17.1} = F = 0.51\%$$

As seen from Table C-10, there was a decrease in algal concentrations from 53.4 mg/l in the effluent of the anaerobic unit to 45.7 mg/l in the effluent of the high-rate pond, and a further reduction to 18.6 mg/l in the settling pond effluent. If these negative values are introduced into equation 2, the calculated light conversion efficiencies will also be negative. This phenomenon was observed at the Concord pond system and indicates that algae are oxidized and/or decomposed at the pond bottom.

On the other hand, because recirculation from the algal pond to the anaerobic pond was used most of the algae in the anaerobic pond could have been grown in the high-rate pond. If this were the case, the efficiency in the high-rate pond would have been 1.29% and the corresponding oxygen production, 65 lbs. per acre day.

Overall System Performance of Spring Conditions. The overall performance data for spring conditions are summarized in Tables XXXIV and XXXV. The data in Table XXXIV shows the performance of the overall system for the most important parameters, i.e., BOD, COD, carbon, nitrogen and phosphate. This table clearly shows the degree of removal of BOD - 97.2%; COD - 92.8%; carbon - 78.8%; nitrogen - 91.6%; and phosphate - 64.3%. This table also indicates that, as previously mentioned, most of the stabilization activity and related nutrient removal rates occurred prior to sampling point 4 with only 42 out of 110 days of detention time.

Table XXXV is a tabulation of current performance data and original

TABLE XXXIV

Overall System Performance (spring conditions)
(values in mg/1)

	Sampling Points						Percent Removal
	1	2	3	4	5	6	
BOD	142.5	22.2	8.2	5.1	2.1	3.9	97.2
COD	307.0	115.8	60.9	39.0	22.7	21.6	92.8
Carbon	131.5	63.4	51.0	42.6	34.8	28.0	78.8
Nitrogen	35.4	11.5	9.5	6.6	5.0	3.1	91.6
Phosphate	11.8	7.5	6.7	5.4	4.4	4.2	64.3

TABLE XXXV

Comparison of BOD Loadings

Pond Unit	Area Acres		Depth Inches		Detention Time Days		Hydraulic Loading $(\frac{d}{\theta})$ inches/day		BOD Loading lb/acre/day		Removal %		Removal Δ %	
	Des.	Act.	Des.	Act.	Des.	Act.	Des.	Act.	Des.	Act.	Des.	Act.	+	-
Anaerobic	2.2	2.2	120	120	14.4	17.1	8.3	7.0	970	226	50	84.4	34.4	
High-Rate	5.0	5.0	36	36	9.8	11.7	3.7	3.1	210	15.5	25	67.0	42.0	
Settling	2.1	2.1	96	96	10.9	13.1	8.8	7.4	380	13.7	60	37.8		22.2
Polishing I	4.3	4.3	156	96	36.0	26.8	4.2	3.6	72	4.2	70	58.7		11.3
Polishing II	5.9	5.9	156	108	50.0	41.4	3.1	2.2	10.5	1.2	70	None		70.0*

*There is actually an increase in BOD

design parameters for BOD for the complete pond system. The design BOD loadings are as estimated for the winery season, and therefore are higher than experienced with domestic BOD during the spring sampling period. However, the detention times are almost identical, and therefore, the comparison seems to be valid. This comparison table indicates clearly that the first two pond units, (anaerobic and high-rate pond) performed above the expectations, and the last three units (settling pond and the two polishing ponds) performed far below expectations.

The Summer Sampling Program. In order to compare pond performance under spring conditions with pond performance under conditions prevailing in summer, a summer sampling program was initiated. As previously described, in the spring sampling program the sewage was entirely domestic and all five ponds were filled and were in operation. During the summer sampling program, however, fruit processing waste was conveyed to the pond system, and only four ponds were at full hydraulic capacity and in operation. Because of the higher evaporation losses in summer, and the normal but high percolation rates, there was no overflow from polishing pond I to polishing pond II in summer. Consequently, the summer sampling program includes only sampling points 1, 2, 3, 4, and 5. The absence of pond 6 indicates there was no overflow from the pond system.

Although polishing pond II contained approximately one foot of pond liquid, it could not be regarded as an operational part of the pond system because it was functioning merely as an evaporation pond, the concentrations of all constituents and salts increasing with evaporation concentration.

In July, before fruit processing wastes reached the pond system, and at a time when only four ponds were full and operational, samples were collected at sampling points 4 and 5 and were analyzed. Both the spring and summer values are given in Table XXXVI. The analysis indicated some differences between the pond system performance in the spring and that in July, but this difference did not change the overall performance picture.

In Table XXXVI it can be seen from the data that nitrogen and phosphate were lower in July than in the spring period, but that BOD and COD had increased. The apparently better nitrogen and phosphate removals seem to be the result of higher temperatures and pH levels, both of which resulted from higher algal growth rates and perhaps brought about higher rates of ammonia volatilization and higher rates of phosphate precipitation. Concentration due to evaporation is believed to have slightly increased BOD and COD. However, there is also the possibility that because of higher rates of sludge digestion in the anaerobic pond, some overflow of organic solids to other pond units may have occurred.

On August 31 a more extensive sampling program was carried out. In this sampling program determinations of the physical, chemical, and biological characteristics similar to those in the spring sampling program were made. The data on temperature, pH, secchi disk readings, volatile suspended solids and chlorophyll for the spring and August sampling periods are given in Table XXXVII.

The higher temperatures and the changes in pH levels as indicated in Table XXXVII reflected the higher algal concentrations in August (based on volatile suspended solids and chlorophyll concentration) than were found either in July or in March or April.

Table XXXVIII was compiled to further compare the overall performance of the pond system under spring and summer conditions. The comparison in Table XXXVIII shows that the overall performance efficiency

TABLE XXXVI

Comparison of Spring Mean with July Conditions[1]
(all values in mg/1)

Sampling Point	BOD		COD		Total-N		$PO_4^{\equiv}$	
	Spring Mean	July	Spring Mean	July	Spring Mean	July	Spring Mean	July
4	5.1	9.9	39.0	65.2	6.6	3.1	5.4	4.9
5	2.1	10.8	22.7	45.8	5.0	3.0	4.4	3.2

[1] Spring mean values for several sampling periods

[2] July mean of duplicate values for single sampling period

No Reference "2" in Table

TABLE XXXVII

Comparison of Pond System Characteristics

Samp. Pts.	Temp. °C		pH		Secchi Disk Readings (cm)		Volatile S.S. mg/l		Chlorophyll[1] mg/l	
	Spring	Aug	Spring	Aug	Spring	Aug	Spring	Aug	Spring	Aug
1			7.2	7.5						
2	17.0	24.0	7.7	7.0	25.4	15.0	53.4	103.0	1.06	2.55
3	17.2	25.0	8.1	7.7	23.6	26.0	45.7	90.4	0.97	1.10
4	16.9	25.0	8.3	9.2	41.6	29.0	18.6	54.6	0.35	0.57
5	16.9	25.7	7.4	9.5	97.6	41.0	3.2	27.5	--	0.20
6[2]	17.7	(30.7)	7.5	(10.1)	--	--	3.7	(242.4)	--	--

[1] Chlorophyll a + Chlorophyll b

[2] Sampling Point 6 is not an operational part of the pond system in summer

TABLE XXXVIII

Comparison of Overall System Performance
(all values in mg/1)

Sampling Points	BOD		COD		Carbon		Nitrogen		Phosphate	
	Spring	August	Spring	August	Spring	August	Spring	August	Spring	August
1	142.5	303.0	307.0	568.0	131.5	300.0	35.4	44.9	11.8	15.9
2	22.2	17.5	115.8	132.0	63.4	225.0	11.5	20.8	7.5	18.8
3	8.2	9.6	60.9	85.9	51.0	125.0	9.5	17.4	6.7	18.7
4	5.1	12.7	39.0	77.2	42.6	95.0	6.6	7.3	5.4	12.7
5	2.1	12.0	22.7	39.9	34.8	65.0	5.0	2.8	4.4	5.3
6[1]	3.9	--	21.6	--	28.0	--	3.1	--	4.2	--
Percent Removal	97.2	96.0	92.8	93.0	78.8	78.2	91.6	93.7	64.3	66.7

[1] Sampling point 6 is not an operational part of the pond system in summer

did not change between the two sampling periods, and indicates that the pond system was able to treat the incoming fruit processing waste together with the normal domestic waste in the summer period. This accomplishment of the pond system is of special interest when the much higher organic loadings expressed in BOD and COD levels are considered. For example, the BOD load of the deep anaerobic pond for the summer period was 480 lb/acre/day. Despite this high loading, all pond units performed satisfactorily.

Additional items of interest in the summer sampling program are described as follows:

1) Because of the higher BOD levels in the influent and the higher temperatures prevailing in August, the organic solids in the deep anaerobic pond were decomposed at a high rate, and anaerobic conditions extended almost to the surface layer of the pond. (In the spring period a five-foot aerobic layer was found to overlie the top of the anaerobic layer). This trend toward more complete anaerobic conditions in the summer month in this period unit is also shown by the data in Table C-1. Odors, however, were almost non-existent. The appearance of the pond surface was different in that a dark green algal layer (despite zero DO readings, however) covered the surface and black anaerobic scum particles from the lower layer could be observed to appear at the pond surface and then to settle.

2) The mechanics by which nitrogen could have been lost from the system is of interest. Ammonia concentrations at sampling point 1 were 30.0 mg/l; at sampling point 2, 10.5 mg/l; at sampling point 3, 6.6 mg/l; at sampling point 4, 0.8 mg/l; and at sampling points 5 and 6, zero. The zero readings at sampling point 5 and in the impounded pond liquid

at sampling point 6 are believed to be indicative of ammonia volatilization. Volatilization would have been enhanced by the higher temperatures and higher pH levels prevailing in the August samples. The temperature at sampling point 5 was 25.7°C and the pH was 9.5. At sampling point 6, the temperature was 30.7°C and the pH was 10.1, conditions which almost certainly would cause loss of ammonia (see Figure 13). Zero readings for ammonia concentrations were also noted in the August 20-21, 1969 sampling program in the Richmond high-rate pond. As stated earlier, high temperatures and high pH readings prevailed in the pond at that time also. There is thus the strong possibility that ammonia volatilization is a significant method of nitrogen emission from these ponds.

3) Although conversion of ammonia to nitrate cannot be ruled out completely, nitrate concentrations were found to be very low. As indicated previously, nitrate concentration was found in the spring sampling program (sampling point 1, 1.02 mg/l; sampling point 2, 0.50 mg/l; sampling point 3, 0.26 mg/l; sampling point 4, 0.33 mg/l; sampling point 5, 0.16 mg/l; and sampling point 6, 0.20 mg/l) were so low that the accuracy of the method of measurement was questioned. As mentioned under "Materials and Methods," the Standard Methods procedure used (phenoldisulfonic acid) is recognized not to be sufficiently sensitive for accurately measuring the small concentrations of nitrate encountered in the present study. Accordingly, the cadmium column method, reported to be most accurate at concentrations as low as to be within the microgram range, was emphasized. Results obtained with the cadmium column method are listed in Table XXXIX. It is evident from the data that while the phenoldisulfonic acid method was not accurate, nitrate values in the system were indeed low.

TABLE XXXIX

Results Obtained with the Cadmium Column
All values in mg/l *

Sampling Point	NO_2^-	NO_3^-
1	0.2	18.1
2	2.3	12.0
3	28.0	15.0
4	2.6	10.5
5	0.0	6.3
6	0.0	8.0

*As indicated Ion

Algal Counts. Algal counts and determinations of the predominant algal species were made in the summer sampling program. Algal counts, the predominant algal species, and the chlorophyll concentrations are summarized in Table XL. As in many ponds, the predominant algal was *Chlorella sp.*

Overall Performance

An evaluation of the overall performance and efficiency of the Saint Helena pond units based on the findings presented in the preceding paragraphs and on treatment efficiency calculations for the spring sampling period is presented in the following section.

Anaerobic Pond. Except under summer conditions, the anaerobic pond functioned as a deep facultative pond having an anaerobic layer of approximately five feet at the bottom, and an aerobic layer of approximately five feet on the top. Depth samples taken on April 29, 1970 indicated a dissolved oxygen gradient ranging from 13.1 mg/l at the surface layer to 1.5 mg/l at a depth of four feet.

The combination of a five-foot anaerobic layer covered by a five-foot aerobic layer resulted in excellent treatment. In addition to good overall BOD and nutrient removal, floatables were effectively removed in the anaerobic layer and odorous gases were oxidized in the top layer. As a result, the so-called "anaerobic unit" was odor-free and had a green scum-free surface. Its overall performance as a sewage treatment unit was outstanding.

Under summer conditions, the five-foot aerobic layer disappeared and the anaerobic bottom layer became much deeper, moving upward to a point near the surface. However, during this period, BOD reduction in this pond unit continued to be very high (up to 90%, and the pond operated with almost no odor production.

TABLE XL

Algal Counts and Predominant Algal Genus

Sampling Point	Algal Count per cm^3	Predominant Genus	Chlorophyll[1] mg/l
2	1.42×10^6	Chlorella	2.55
3	1.30×10^5	Chlorella	1.10
4	1.00×10^5	Chlorella	0.57
5	1.00×10^4	Chlorella	0.20
6[2]	7.3×10^4	Microcystis	--

[1] Chlorella + Chlorella

[2] Sampling point 6 is not an operational part of the pond system in summer

High-Rate Pond. As noted previously under the current operational regimen,the high-rate pond has a surface area of 5.0 acres and only one pump in continuous operation. As a result, the flow-through velocity in the pond channels is only 0.16 feet per second. In regards to treatment performance, the combination of these two factors, the big area and only one pump in operation, is negative. Nevertheless, BOD removal was good, i.e., 67.0% in spring and 43% in summer. Nitrogen and phosphate removals were less than expected, i.e., 17.4% for nitrogen and 11.3% for phosphate in spring and only 15.4% for nitrogen and 0.5% for phosphate in summer. The reductions measured on a lb/acre/day basis as shown in Tables XXXI and XXXII were also relatively low.

Settling Basin. The available data indicate that the performance of the settling pond was only fair. This pond was not as effective as the preceding two pond units in treatment since there was little left to treat. However, the reduction of BOD and nutrients was measurable, and consequently the settling pond performed well enough to be regarded as a useful part of the complete pond system. Inasmuch as its function was to have been sedimentation in the design of future pond systems, it may be worthwhile to precede the deep settling ponds with ponds shallower than used herein in order to improve nutrient fixation and removal. Such shallow ponds could be operated at depths or low as four to eight inches in order to raise the pH levels sufficiently high to cause phosphate precipitation (about pH 10.5 - see Figure 27), and ammonia release to the atmosphere (see Figure 13). Addition of chemicals to the ponds could also perhaps further enhance precipitation rates and nutrient removal and should be investigated in the future in connection with settling basins or other methods of separation such as centrifugation or filtration.

Polishing Pond I. The expression "polishing pond" is an apt term for this element of the system insofar as BOD removal is concerned, but it is less so for nutrient removal.

As previously described, in winter months this pond is populated by daphnia which strain out the algae from the pond liquid. In the summer months explored algae and daphnia populations were found to succeed each other in cycles, but generally algae dominated. Because of the daphnia population in the polishing pond, BOD removals to the low levels of plus or minus 5.0 mg/1 were being achieved. This degree of BOD removal is believed to result from the presence of daphnia which feed on bacteria and suspended matter and hence in effect filter the liquid. This type of polishing effect of the daphnia and other filter feeders is well known and hence to be expected whenever these organisms are present in ponds. However, during the summer, daphnia populations were low and the pond effluent was still of good quality indicating that daphnia are not the only organisms involved. As might be expected, nutrient removals were low or nonexistent in the polishing pond units probably because those organisms feeding on algae excreted their nutrients in soluble form thus reversing the nutrient fixation achieved earlier in the system.

Polishing Pond II. The treatment capability of this pond unit was found to be poor. It is only in use during the winter and spring months and hence is an intermittent basin. When in operation, this pond's efficiency appears low not only because influent quality is high but because the pond is a final depository for solids. As is indicated by the results recorded during the spring sampling period (March and April): 1) BOD increased from 2.1 mg/1 to 3.9 mg/1; 2) nitrogen decreased from

5.0 mg/1 to 3.4 mg/1; and 3) phosphate decreased slightly from 4.4 mg/1 to 4.2 mg/1. These are very poor results for 41.3 days of detention time. The location of the sampling pond (on the shoreline and not on a bridge structure) undoubtedly influenced the results in a negative way, but they did not change the overall picture.

The function of polishing pond I and especially of polishing pond II is more as a storage-percolation basin. This means that substantial amounts of winter flows can be stored in the polishing pond and later in spring and summer months the water introduced percolates into the ground. The storage-percolation action of the polishing pond lessens the burden on the Napa River, and probably to some extent enriches at the same time the water in the local groundwater basin. It should be noted, however, that the volume of water escaping from the pond during a given year is small.

ANCILLARY LIGHT-BOX STUDIES

Ancillary light box studies were carried out in order to confirm findings made in the previous light box studies of optimization of nutrients for the growth of algae or for prediction of their potential growth in a given waste. The pond liquids used were from Concord and Saint Helena. In the earlier studies, the two liquids were not tested simultaneously, the Concord pond liquid being tested approximately five months prior to the Saint Helena pond liquid. To account for chance differences due to the time lapse between the two runs, the two pond liquids were tested simultaneously in the present light-box study. In the present light-box study, as in the previous light-box studies, the need for adjusting the C and N nutrient ratios was investigated.

Procedures

Samples were collected on November 8, 1970 from the Concord and the Saint Helena stabilization pond systems. At Concord, the samples were taken at sampling points 3, 4, and 5; and at Saint Helena from sampling points 3, 4, and 5. Weather conditions on the day of sampling, which occurred two days after a rainstorm, were cool and cloudy (see temperature and pH readings in Table D-1 in the Appendix). The Analyses of the samples, as given in Table D-2, indicated again the presence of low carbon concentrations in relation to nitrogen and phosphate concentrations in the pond liquid. For example, the C/N ratios of the Concord samples were 1.7 at sampling point 3, 3.3 at sampling point 4, and 2.4 at sampling point 5. The C/N ratios of the Saint Helena samples were 2.1 at sampling point 3, 2.8 at sampling point 4, and 10.2 at sampling point 5. The low C/N ratios at sampling points 3 and 4 in Saint Helena (lower than those found in the spring and summer sampling periods) seem to reflect different types of wastes than those which reached the pond system during the fruit processing season in August, September, and October.

Based on their carbon and nitrogen concentrations (see Table D-2) pond liquids collected from sampling points 3, 4, and 5 in Saint Helena, and from sampling point 5 in Concord, were chosen for the light-box studies. As previously mentioned, the C/N ratios at the three Saint Helena sampling points differed from each other (from 2:1 to 10:2); and thus different growth patterns with combinations of adjusted and unadjusted pond liquid of one system could be tested. In the Concord pond system, all samples had low C/N ratios (from 1.7 to 3.3) and here only the pond liquid from sampling point 5 was tested. In the system as it is operated, the detention time is longest at this point, namely 6.7 days.

The pond liquid was first centrifuged and than filtered through a glass mat filter (pore size 0.5-1.0u) to remove algal and other particulate matter. The filtered pond liquid was inoculated by adding 10 ml of an inoculum of algae to a 2.1 liter aliquot of each sample. The inoculum was taken from one of the high-rate ponds at the Richmond Field Station. The cell count of the inoculum was 5.6 x 10^6/ml as determined with the use of a haemocytometer, and 7.6 x 10^6/ml as counted by means of a Coulter counter. Since the Coulter counter senses all particles, and since counting by way of a haemocytomer lacks a certain degree of accuracy, the average number of the two was used, namely, 6.6 x 10^6/ml. Two-hundred ml aliquots of each of the inoculated samples were then placed in 500 ml Erlenmeyer flasks. On the basis of the cell count of the inoculum and the ratio of inoculum to medium, the cell count/flask was estimated to be 6.25 x 10^6 cells (3.12 x 10^4 per ml of medium).

For each sample, three of the inoculated flask cultures served as controls. In addition, the C/N ratio of the cultures in the remaining six flasks was adjusted to 8. The samples from sampling points 3 and 4 in Saint Helena, and those from sampling point 5 in Concord were adjusted to a C/N ratio of 8 by the addition of sodium bicarbonate. The adjustment of the C/N ratio of the sample from Saint Helena sampling point 5 (C/N ratio of 10.2) was made by adding ammonia chloride. The addition of bicarbonate to the samples was accompanied by an increase in pH to levels between 9.5 and 9.9. To bring the samples with the adjusted C/N ratios to a pH level equal to that of the controls, the pH of three of the remaining six flasks (with a C/N ratio of 8) was readjusted to that of the controls. The pH of the other three flasks (of each group of six with a C/N ratio of 8) was not adjusted and thus remained at the high 9.5 to 9.9 levels. Since no pH changes occurred after adding ammonia chloride to the pond liquid from sampling point 5 in Saint Helena, no pH adjustment was necessary, and consequently only six flasks (i.e., three controls and three with adjusted C/N ratios) were used for this sampling point. In Table D-3 are summarized the "zero-time", C/N ratios, and pH levels of the various flask cultures. The flasks were placed in a light box illuminated with 1 horizontal 30-watt cool white fluorescent lamp and were allowed to remain there for a period of 13 days. Temperature and pH were measured daily, and at the time of each reading, the flasks were rotated in position in the box and mixed by swirling the flasks.

The temperature of the cultures in the flasks containing the samples from Concord 5 ranged from 25.5°C to 30.5°C during the 13-day test run. The temperature range of the cultures in the Saint Helena 3 flasks was from 24.5°C to 28.2°C; in the Saint Helena-4 flasks, from 25.1°C to 28.6°C; and in the Saint Helena-5 flasks, from 25.0°C to 27.0°C. The recorded pH levels for the sets of control flasks, for the four samples were in the range of 8.0 to 10.95. The flasks having the C/N ratios of the medium in them adjusted to 8 showed a wider range of fluctuation in that the pH levels ranged from 7.70 to 11.65. A few hours after the addition of bicarbonate (for C/N adjustment) and placing the Concord-5 flasks in the light box, the pH level reached the 9.9 mark and a cloudy precipitate appeared. After three days the cloudy precipitate disappeared, and the cultures took on a green color--indicative of active algal growth. The relatively high degree of hardness of the Concord pond liquid apparently resulted in a reaction with the bicarbonate, thereby forming some type of precipitate (probably $CaCO_3$). The addition of hydrochloric acid to a second set of flasks of the Concord-5 (C/N 8) for pH adjustment was not accompanied by a cloudy appearance.

Results

Algal growth is reported in terms of increase in volatile solids and chlorophyll concentrations. With the exception of Concord-5 samples in which C/N ratio was adjusted to 8 and the pH level was not adjusted, the percentage of volatile solids as algae ranged from approximately 75% to 90%. The percentage of algae in the aforementioned Concord-5 samples was on the order of 50% to 70%. The results are given in detail in Tables D-4, D-5, D-6, and D-7, and are shown in a summarized form in Table XLA.

Because of prolonged high pH (10 days and more) during the test run, the chemical equilibrium in the samples changed and gas exchange must have taken place, especially of CO_2. This phenomenon was noted in all flasks, including the control flasks in which pH range was lowest (9.80 to 10.95). In the control flasks, as in all the other flasks, the final total carbon concentrations, because of prolonged CO_2 absorption at high levels, exceeded the initial carbon concentrations. Because with the limited facilities and resources available, it was not feasible to attempt to account for the carbon diffused into the cultures as CO_2 or lost as precipitated CO_2 due to the high pH levels of the cultures. These same constraints also apply to determining nitrogen loss as volatilized NH_3 and as precipitated ammonia-calcium-phosphate complexes and phosphorus loss as PO_4 precipitate, - again because of the high pH levels. Thus, it was also impractical to try to arrive at nutrient balances for the cultures.

TABLE XLA

Final Volatile Suspended Solids and Chlorophyl Concentrations for Ancillary Light-Box Studies
(values given are means of three flasks)

Sampling Point	Vol. Sus. Solids				Chlorophyl			
	Control	Adjusted	Vrs. Control		Control	Adjusted	Vs. Control	
	mg/1	to C/N 8	mg/1	%	mg/1	to C/N 8	mg/1	%
Saint Helena 3	131.9	220.8	+88.9	+67.3	0.91	2.03	+1.12	+121.9
Saint Helena 4	126.0	148.3	+22.3	+17.7	0.43	1.07	+0.64	+146.7
Saint Helena 5	59.7	71.5	+11.8	+19.8	0.17	0.23	+0.06	+35.5
Concord 5	200.9	320.2	+119.3	+59.4	2.86	3.52	+0.66	+11.4

The results as given in Table XLA reconfirm earlier findings in this study, and indicate again that the adjustment of C/N ratios to those found normally in the composition of algae enhance algal growth, and consequently, the related nutrient uptake. With the exception of cultures having the cloudy precipitate, i.e., Concord 5, chlorophyll concentrations were substantially higher in those cultures in which the C/N ratio was adjusted to 8. The higher chlorophyll concentrations are indicative of increased algal production in these flasks, since conditions other than C/N were equal.

Three findings of the ancillary light-box studies are of particular interest. They are:

1) The increase in algal growth with adjusted nutrient ratios in samples taken from the Saint Helena stabilization pond system and in samples taken from the Concord stabilization pond system indicates that C/N ratio adjustments had favorable results at different points in the stabilization pond systems and in stabilization ponds of different design, operation, and performance characteristics.

2) In the Saint Helena-5 sample, the original C/N ratio of 10.4 was adjusted with ammonia chloride to an C/N ratio of 8.0. This downward adjustment, although small, resulted in an increase in algal growth in the same order of magnitude as occurred in samples in which the initially low C/N ratios (2.1 to 2.8) were adjusted upward.

3) The increase in algal growth was greater in samples with higher nutrient concentration and favorable C/N ratios (higher algal growth potential), as is shown in Table XLA for the samples from Saint Helena-3 and Concord-5.

From the results obtained in this light-box study, it can be concluded that the adjustment of nutrient in terms of C/N ratio would have a highly significant effect on the enhancement of algal growth in a stabilization pond and hence a beneficial effect on its performance. Consequently, this nutritional "tool" should be further studied, developed, and actually applied to operational stabilization ponds.

The results also confirm the concept that these biological unit processes are greatly influenced in performance by the nutritional quality of wastes and, hence, by their position in a series of processes.

V. GENERAL DISCUSSION

COMPARISONS AND EVALUATIONS

Stabilization Pond Systems with and without Preceding Treatment Plants

A question of great importance is the correct position of ponds in wastewater treatment processes. Pond systems are often designed to follow conventional treatment plants and to function as secondary and tertiary treatment units, or they may be designed to carry out all of the treatment functions by themselves. The question arises as to which position is superior. The evidence presented in this dissertation clearly shows that the performance of a stabilization pond system depends to a large degree on its position in the overall system and, hence, an answer to the position question demands that all alternatives be explored. The systems observed and reported on in this dissertation were not necessarily ideal for this investigation but were the only ones which had in common the incorporation of a growth unit designed specifically for algal growth and were readily accessible for study.

This performance comparison between the Richmond system, the Concord pond system and the Saint Helena pond system has shed some light on that question. As previously described, Richmond had primary sedimentation ahead of the high-rate pond, Concord has a conventional treatment plant preceding the stabilization pond system, and Saint Helena has no treatment ahead of the ponding system. The Concord and the Saint Helena pond systems are similar in that they consist of an anaerobic pond, a high-rate pond, and a polishing unit. However, there is an extremely large difference in the detention time between the two pond systems, Saint Helena having a nominal detention period of 110 days and Concord, only 6.9 days. Because of interruption in flow, the Richmond system has an indeterminant detention period, and, thus, is excluded from the following comparisons.

In the following table (Table XLI), a comparison is made between the Concord and Saint Helena systems in regards to BOD and nutrient removal efficiency. The first and most important comparison is between sampling points 1 and sampling points 2 of both systems, that means between the conventional treatment plant in Concord and the deep anaerobic pond in Saint Helena. As is seen from the data in Table XLI, the BOD and T-C removal efficiencies of both systems were comparable, although a slightly higher BOD removal efficiency for the Concord treatment plant can be noted. In the case of nitrogen and phosphate removals, the deep anaerobic pond in Saint Helena accomplished effective nutrient removal (67.5% of nitrogen and 36.3% of phosphate). The Concord treatment plant, however, did not have such nutrient removal capabilities (17.3% nitrogen removal, and a slight increase apparent in phosphate).

Because of the differences in nutrient removal, the changes in nutrient ratios were also different. The C/N ratio in the Concord treatment plant decreased from 5.17/1 to 3.32/1, i.e., from a normal range of algal growth to an unfavorable range, whereas the C/N ratio in the Saint Helena deep anaerobic pond increased from 3.71/1 to 6.10/1, i.e., from a range that is considered unfavorable for algal growth to a normal range. This seems to be a significant difference which favors the deep anaerobic pond in Saint Helena as a nutrient removal system.

In comparing the two pond systems overall, i.e., the Concord pond system between sampling point 2 and 5, and the Saint Helena pond system between sampling point 1 and 6, the following differences are noted. BOD and T-C removals were comparable although with better T-C removals in the Saint Helena pond system. As shown in Table XLI, nutrient removal

TABLE XLI
COMPARISON OF PERFORMANCE OF THE CONCORD AND SAINT HELENA POND SYSTEMS

Samp Point	Treatment Unit		Det. (days)		BOD (mg/1)		T-Carbon (mg/1)		T-Nitrogen (mg/1)		Phosphate (mg/1)		C/N		C/P		N/P		Alkalinity (mg/1)	
	Concord	St. Helena	C[1]	S.H.[2]	C[3]	S.H.	C	S.H.	C	S.H.	C	S.H.	C	S.H.	C	S.H.	C	S.H.	C	S.H.
1	Primary & Secondary Treatment	Deep Anaerobic Facultative Pond	0.2	17.1	152.8	142.5	160.0	131.5	30.9	35.4	10.1	11.8	5.17	3.71	15.70	11.14	3.06	3.00	222.0	158.0
2	Anaerobic Pond	High-Rate Pond	1.6	11.7	20.0	22.2	85.0	63.4	25.6	11.5	10.9	7.5	3.32	6.10	7.80	8.45	2.34	1.38	214.0	107.0
3	High-Rate Pond	Settling Pond	2.4	13.1	18.5	8.2	88.0	51.0	28.6	9.5	12.1	6.7	3.08	5.37	7.25	7.65	2.36	1.42	226.0	99.0
4	High-Rate Polishing Pond	Polishing Pond I	2.7	26.8	6.0	5.1	70.5	42.6	29.1	6.6	12.2	5.4	2.42	6.45	7.76	7.82	2.38	1.21	228.0	94.0
5	NCM	Polishing Pond II	--	41.3	5.2	2.1	78.0	34.8	28.6	5.0	12.9	4.4	2.72	6.96	6.05	7.94	2.22	1.14	238.0	87.0
6	Total		6.9	111.0	--	3.9	--	28.0	--	3.1	--	4.2	--	9.03	--	6.68	--	0.74	--	72.0

[1] Concord

[2] Saint Helena

[3] Yearly mean

was ineffective in all the ponds of the Concord pond system. In the Saint Helena pond system, however, effective nitrogen and to a certain degree effective phosphate removal occurred in all pond units. The major reasons for the differences in nutrient removal between these two pond systems are believed to be that: 1) The longer detention time in the Saint Helena pond system provided a longer reaction time for algae and other agents to fix ammonia or for physical processes to release ammonia to the atmosphere, and to precipitate phosphate. This seems to be especially important for nutrients in inorganic forms. 2) The nitrogen losses from the deep anaerobic unit in Saint Helena made possible an improved nutrient ratio in the pond liquid (C/N and C/P), and the balanced nutrient supply stimulated algal growth in the succeeding pond units. The Concord treatment plant by removing mainly carbon from the sewage caused an imbalance in the nutrient supplied for algal growth in the succeeding pond units. 3) The quantity of light was greater during the Saint Helena sampling period (spring of 1970, approximately 190 gram calories/cm^2/day) than during the sampling period in Concord (approximately 125 gram calories/cm^2/day in late fall and early winter, 1969). Because of the better light conditions and the balanced nutrient supply, a mean algal concentration of 45.7 mg/liter was found in the Saint Helena high-rate pond, whereas because of less favorable light conditions and an imbalance in nutrients, the mean algal concentration in the Concord high-rate pond was 35.3 mg/liter.

Lined Versus Unlined High-Rate Ponds

Design and Operation Concepts.

When the basic principles for the design of high-rate ponds were first set forth (37), light penetration and mixing were considered major factors in the list of design and operation parameters. To permit the attainment of optimum levels in these parameters, the high-rate pond constructed at the Richmond Field Station was supplied with a hard surface lining. Because of the lining, mixing did not cause unwanted turbidity, and light utilization was maximal at a depth of 8 to 12 inches. On the other hand, because of budgetary problems, the high-rate ponds in Concord and Saint Helena were left unlined, and were operated at depths in the range of 3 to 3½ feet. Considering that BOD removal was the main objective for Concord and Saint Helena unlined, high-rate ponds, these design and operation parameters were sound. In other words, when algal production and nutrient removal are the objective, shallow lined ponds are required, but if only BOD removal is desired, deeper unlined ponds are adequate.

The Protective Sludge Layer. When the two high-rate ponds in Concord and in Saint Helena were studied (as part of the present research program), it was found that a microbial sludge-slime layer covered the pond bottoms. It was also observed that the forced flow by pumping and the related velocities did not cause unwanted turbidity. The mean velocity of the high-rate pond in Concord was 0.28 ft/sec, and the mean velocity at the Saint Helena high-rate pond was 0.16 ft/sec.

No measurements of velocity distribution throughout the cross section of the high-rate pond were made. However, from basic hydraulic principles of water flow in channels and streams, the general velocity distribution can be established. Such a velocity distribution undoubtedly would show lower-than-average velocities near the baffle walls and pond bottom, and higher velocities at the pond surface (75). The lower velocities at the pond bottom together with the presence of oxygen allows the development of a sludge-slime layer which protects the bottom from erosion and also possibly acts in nutrient release and to buffer the high pH levels reached in the upper layer of the ponds.

Nutrient Release. Settled suspended solids of sewage origin, algal and/or other microorganisms accumulated and are finally decomposed in the active bottom sludge layer with consequent nutrient release into the lower strata of the pond liquid. These recycled nutrients then become mixed with the overlying strata where they are available for algal growth and another round of sedimentation.

Buffering of pH. From the data presented, it appears to be that, generally, unlined, deep high-rate ponds are characterized by a higher degree of stability than are lined, shallow high-rate ponds. A shallow lined high-rate pond at Richmond was observed to have a repeated die-out of algae, whereas, the deeper unlined ponds in Concord and at Saint Helena have showed no such algal die-out. To explain this, there appear to be three cases: stratified facultative ponds; deep, mixed, unlined ponds; and shallow, mixed, lined ponds.

In facultative ponds characterized by stratification, the sludge layer at the bottom is less influenced by climatic conditions (from the atmosphere) than is the upper liquid layer. The bacteria (mainly anaerobic) grow, therefore, in an environment protected from rapid changes with relatively stable growing conditions. In the summer when algal activity increases and the pH tends to rise, the bacteria in the sludge layer continue to produce sufficient CO_2 and organic acids to buffer the system and thereby pH levels are maintained in favorable limits. For example, as noted in the literature survey (28), in the facultative pond at Herzliya, Israel, despite high summer temperatures of 25-28°C, the mean pH levels remained within the range of 8.0 to 8.1, and only during the day were somewhat higher pH levels observed. These low pH levels indicate that the accumulated sludge with the related bacterial activity in a facultative pond was strong enough to stabilize the pond liquid in regards to pH.

In unlined, deep high-rate ponds, a less distinctive but still highly active bacterial sludge-slime layer develops on the bottom. Except for the fact that it may be partially aerobic, the sludge-slime layer seems to act in almost the same manner as the sludge layer in a facultative pond; that is, it releases nutrients for algal growth and also releases buffer substances which prevent the pH from rising as a result of algal activity.

In the case of the shallow, lined high-rate pond at the Richmond Field Station, photosynthetic activity is so intensive that in spite of the buffering action of the sludge layer at the bottom the pH rises to high levels. This, in turn, causes a decrease in biological oxidation depriving algae of nutrients.

The stabilizing effect of bottom sludge on pH has not received the attention it deserves in the theory of ponds. The results of the present study confirm the hypothesis that the algal-bacterial symbiosis in ponds is both a symbiosis of oxygen supply from the algae to the bacteria and a nutrient supply from the bacteria to the algae but further indicates the importance of bacteria in producing substances which neutralize pH levels in anaerobic ponds and in facultative ponds. In addition to the production of inorganic buffers, the data in this study are also believed to indicate that bacteria possibly release organic substances into the pond liquid which prevent the rise of pH to undesirable levels. A search for or definition of the nature of such substances is, however, beyond the scope of this dissertation.

Summary. From the data obtained in this study regarding unlined ponds, it can be seen that when BOD removal is the main objective, relatively deep unlined high-rate ponds can be used successfully and, hence, the need for lining is obviated. Indeed, the presence of a sludge-slime layer acts to stabilize the surface and prevent erosion and, in addition, contributes to the overall pond purification process and the buffering of changes in pH induced by photosynthethis and other microbiological activities.

In terms of operational procedures and problems, the shallow lined high-rate pond which maximized photosynthetic activity should be placed somewhere between a completely controlled laboratory algal growth unit and an unlined high-rate pond. This means that a lined high-rate pond, regardless of being outdoors and exposed to outdoor environmental conditions, will have to be controlled to a higher degree than has been the case in the past. This control should probably include 1) mixing during the day in summer and mixing at night during the winter; 2) depth control, with shallower depth in winter and a greater depth in summer; 3) pH control and nutrient adjustment with CO_2. Therefore, the addition of CO_2 or carbon into the system as employed in the Firebaugh project (18, 119) is a step in the right direction because it would increase the amount of CO_2 available both buffering the system and providing the carbon needed to remove additional nitrogen. Lining of even shallow high-rate ponds may not be necessary. The slimy sludge found at the bottom of the high-rate ponds seems to be composed of polysaccharides (110) comparable to the capsule (slime layer) surrounding the cytoplasmic membrane of a bacterial cell, thus forming a biological cement between soil particles. Another mechanism may also be important. Brock (111) describes the phenomenon of microorganisms attached to solid surfaces as follows:

> "Some bacteria and many protozoa and algae produce structures called holdfasts which are responsible for their ability to adsorb to inert surfaces. These holdfasts are probably polysaccharides; they behave like glue, but their chemical nature and the basis for their adhesiveness is unknown."

The accumulation of millions of these holdfasts and other organic detritum could constitute a slime layer of considerable structural strength and quite adequate to prevent erosive disruption of the pond bed due to hydraulic mixing. There is little doubt that this sludge slime layer acted significantly in the prevention of erosion in the unlined mixed high-rate ponds of Saint Helena and Concord.

Comparison of Anaerobic Ponds

In this section a comparison is made between the apparently poor performance of the anaerobic pond in Concord and the apparently very effective performance of the Saint Helena anaerobic pond. In general the performance seems to be related to solids concentration, inlet position, detention time and degradeability of the organic matter.

Solids Concentrations. At the time the pond systems were observed, the anaerobic pond at Saint Helena received raw sewage having a total suspended solid concentration of 149.2 mg/l; whereas the total suspended solid concentration in the clarifier effluent discharged into the Concord anaerobic pond was only 39.0 mg/l. In terms of the solid carbonaceous fraction in the influent of the two ponds, we find a 56.3% solid carbonaceous fraction in the influent at the Saint Helena anaerobic pond (sampling point 1 in Table XXIV), but only a 24.0% solid carbonaceous fraction in the influent of the Concord pond (sampling point 2 in Table XVI). From soil biochemistry, from activated sludge and trickling filter studies, and from present studies at Firebaugh (119), it has been found that biological activity and the buildup of biomass is enhanced when stable surfaces are available for the biomass to adhere to. In other words, the much higher solid concentrations and the dense sludge layer in the Saint Helena anaerobic pond seems to have been a major factor in the excellent BOD removal performance of the Saint Helena anaerobic pond as compared to the relatively poor performance of the Concord pond.

Parker (116) in his studies at the Melbourne stabilization pond system summarizes his view of the influence of solids in anaerobic ponds as follows:

> "These investigations have shown the beneficial function of sludge solids on lagoon performance in the anaerobic environment."

Saint Helena's excellent performance compared with that of Concord tends to confirm this view.

Inlet Structures. In the Saint Helena anaerobic pond the inlet pipe and the distribution baffles are at the 10-foot deep pond bottom, consequently the incoming sewage has to move through the five-foot thick sludge layer. This five-foot thick sludge layer seems to act as a filter where effective enzymatic surface actions can take place. It was also noted that the surface of the deep anaerobic pond was almost free of floatables. The possibility is that these floatables are trapped in the sludge layer when the raw sewage moves through the five-foot thick sludge layer.

In the case of the Concord anaerobic pond, the inlet pipe is at the pond surface and, consequently, there is no opportunity for the incoming sewage to be exposed to the anaerobic bottom solids. Consequently, because less contact between the incoming sewage and the bottom sludge particles exist, less effective treatment is the result.

Detention Time. Even if a lack of submerged surfaces and a lack of sludge filtration were not detrimental in Concord, the short detention time of only 1.5 days of the Concord anaerobic ponds would probably be insufficient for full development of anaerobic bacteria in the treatment unit. As a result, released nutrients from the degraded suspended solids and the digested aerobic bacteria from the trickling filter which precedes the Concord pond are to some extent displaced into the high-rate pond causing the apparently poor performance.

Degradability of Organic Material. In the case of Saint Helena, most of the organic material applied to the anaerobic pond is easily degradable. That is, it contained large amounts of organic carbon. The organic material applied to the Concord anaerobic pond, however, had already undergone stabilization through trickling filtration and, hence, was composed mainly of stabilized organic matter and was low in organic carbon. Thus, even if all other factors had been equal, the material discharged to the Concord anaerobic pond could not have been treated as effectively as the organic matter discharged to the Saint Helena anaerobic pond.

To summarize, the combined effects of low solid concentration, lack of a submerged inlet, the change from aerobic bacterial populations to anaerobic bacterial populations, the short detention time, and the stability (low carbon content) of the organic matter applied, reduced the treatment efficiency of the anaerobic pond in Concord as compared with that of Saint Helena.

The Position of High-Rate Ponds in Relation to Other Treatment Units

Similar to a complete stabilization pond system, high-rate ponds by themselves depend to a large degree on their position in the treatment process. Therefore, an attempt is made to compare the three high-rate ponds under investigation in regards to their position to other treatment units.

The Richmond high-rate pond is operated as a secondary treatment unit after a settling tank in which the detention time is approximately 1.5 hours. The pond is lined and is maintained at an 8-inch depth. The Saint Helena high-rate pond also is operated as a secondary treatment unit, but it is placed after an efficiency anaerobic pond having a 17-day detention time. The pond is unlined and is held at a 3-foot depth. The Concord high-rate pond is operated as a tertiary treatment unit following a primary settling tank, a trickling filter, and a secondary clarifier, and a short detention period anaerobic pond.

On the basis of the available evidence, it is believed that the Richmond high-rate pond is in a poor position. Because of the short detention time in the preceding settling tank, almost no bacterial breakdown of organic matter takes place in the settling tank; consequently, almost all of the bacterial breakdown of organic matter must take place in the high-rate pond. Because of the shallowness, high pH values occur during the greater part of the year, and aerobic bacterial oxidation is hampered by the high pH. As a result, undecomposed organic solids accumulate, the algae are deprived of nutrients, and BOD removal rates are reduced. Turbidity, due to accumulated solids, also adversely affects algal growth. The irregularity in sewage flow or sewage supply (because of pump failures and irregular use of other research units) results in a variable loading and consequently a varying environment which is detrimental to the effective performance of the high-rate pond.

The Concord high-rate pond is better situated with respect to position in that it receives a steady flow of well-oxidized sewage; however, there is a serious lack of organic carbon in the filter effluent. Nutrient imbalance and short detention time in the preceding anaerobic pond cause nitrogen and phosphate concentrations to remain constant or to increase slightly, thus further contributing to poor nutrient removal. In summary, BOD removal is relatively good, but nutrient removal is poor.

The Saint Helena high-rate pond follows an anaerobic pond unit with 17 days detention time and its serial position appears to be correct as reflected by both good BOD and good nutrient removal.

Comparison of Stabilization Pond System

In making this comparison, an analysis will be made of the collective characteristics of the Melbourne stabilization pond system in Australia, the Herzliya stabilization pond system in Israel, and the Saint Helena stabilization pond system (the most representative one from our study) in California. These three pond systems should be roughly comparable because they are all located in areas with Mediterranean-type climates.

Each of these stabilization pond systems consisting of a number of ponds in series which for purposes of this comparison may be divided into three basic units, an anaerobic-bacterial unit at the influent end, a following algal unit, and lastly, a polishing-grazing unit.

In examining the data from these systems, it becomes very evident that the greatest degree of microbial and chemical activity, as well as the most extensive nutrient reduction can be observed to take place in the anaerobic pond unit. The microbial activity and the related chemical changes in the algal pond unit are less pronounced. In the polishing or grazing units, these changes and activities are almost non-existent.

The above-mentioned changes have a pronounced effect on the nutrient balance (expressed by C/N and C/P or BOD/N and BOD/P ratios) in the three basic units of a stabilization pond system. These nutrient balance changes are greatest in the first unit and least in the last unit.

In all three stabilization pond systems analyzed, BOD reductions were achieved; however, the reduction of nitrogen and phosphate differed among the units.

The Saint Helena stabilization pond system exhibited by far the best nutrient reduction. This superiority is believed to be due to the special inlet and distribution structure of the anaerobic pond, and to the depth of this pond. As previously mentioned, in the Saint Helena anaerobic pond, the inlet is at the bottom between submerged baffles, thus protecting the incoming sewage from exposure to aerobic conditions. In addition, the depth of the pond ensures a stable temperature and pH level both of which are very important for anaerobic decomposition. The stable solid surface in the deep sludge layer are also believed to be an important factor for the excellent performance of this pond.

The ecological changes throughout the pond system are similar in all three systems. In the first unit, there is a decline in the number of bacteria and an increase in algal cells. In the second unit, algal concentrations are at peak levels and bacteria are at sufficient levels to accomplish a further and more refined treatment of the pond liquid. The decline in algal concentrations and increase in number of grazing organisms characterize the third unit where additional treatment and nutrient removal is limited.

The Saint Helena pond system operated at the lowest temperature during the spring sampling program, the mean value being 17.0°C. The mean temperature of the Melbourne system was 21.0°C, and that of the Herzliya system was 26.5°C. The low mean temperature of the Saint Helena pond system during the study period may have been influential in permitting the large daphnia populations observed in this pond system.

Aging - sludge accumulation is one phase of the natural aging process of a water body, and this aging process will undoubtedly influence pond operation in the long run. In a stabilization pond system such as the one in Saint Helena, the first anaerobic unit will undoubtedly have sludge accumulation and some cleaning will have to be provided over the years. The problem and rate of sludge accumulation in pond units other than the primary unit is not known. At present, sludge accumulation does not seem to be a problem in the polishing ponds. However, in the future, the release of nutrients from sludge (consisting of decomposed algae, daphnia, and fecal pellets released from the daphnia digestion system) into the overlaying pond liquid is expected to become a problem. Such nutrient releases will doubtedlessly interfere with the BOD and nutrient removal capability of polishing ponds over the years.

From Laboratory to Pilot Plant and to Outdoor Operation

Since the introduction of algae into the area of sewage treatment, many studies with laboratory pilot plants and outdoor units have been carried out. It is the intention of this short paragraph to indicate factors which should be considered in applying the data and experience from smaller units to larger units.

In a lake the large water volume, slight mixing, CO_2 supply from the atmosphere at night, natural buffer systems, and fresh nutrient supply from deeper layers are in general sufficient to overcome algal cell inactivation and algal cell injuries resulting from high pH levels and nutrient deficiencies during hot summer days. Smaller bodies of water such as ponds are generally shallow, have smaller surface areas and volumes than lakes. Mixing, CO_2 supply, and other natural buffers are, therefore, less effective and become more sensitive to weather conditions.

In laboratories most of the experiments are carried out with constant environment, continuous mixing and controlled nutrient supply, and thus clear relationships may be observed between algal growth and environmental parameters. However, in the pilot plant study in Richmond in the years 1957-59 (37), the problem of the sensitivity of systems to environmental changes was observed. This sensitivity was basically reflected in high fluctuations in many parameters typified by changes in pH levels as shown in Figure 46. These fluctuations are functions of varying degrees of algal activity as influenced by differences in depth of pond cultures. A similar sensitivity was observed at the larger high-rate pond in Richmond when the two 24-hour runs reported herein were conducted. Sensitivity is also reflected in pH fluctuations (see Figure 5) which may become so great that they actually lead to pond failure as described in Chapter IV.

In the Concord and Saint Helena pond systems, problems resulting from pH sensitivity were not observed. The Concord high-rate pond has, in addition to having a larger volume ($3\frac{1}{2}$ feet deep), a high alkalinity and exhibited extremely stable pH levels. It is of interest to note that nutrients were not removed in the Concord high-rate pond, and the possibility of a relationship between the absence of nutrient removal and existence of a stable pH seem to exist. The biggest pond volumes among the three systems studied were those of Saint Helena. As previously

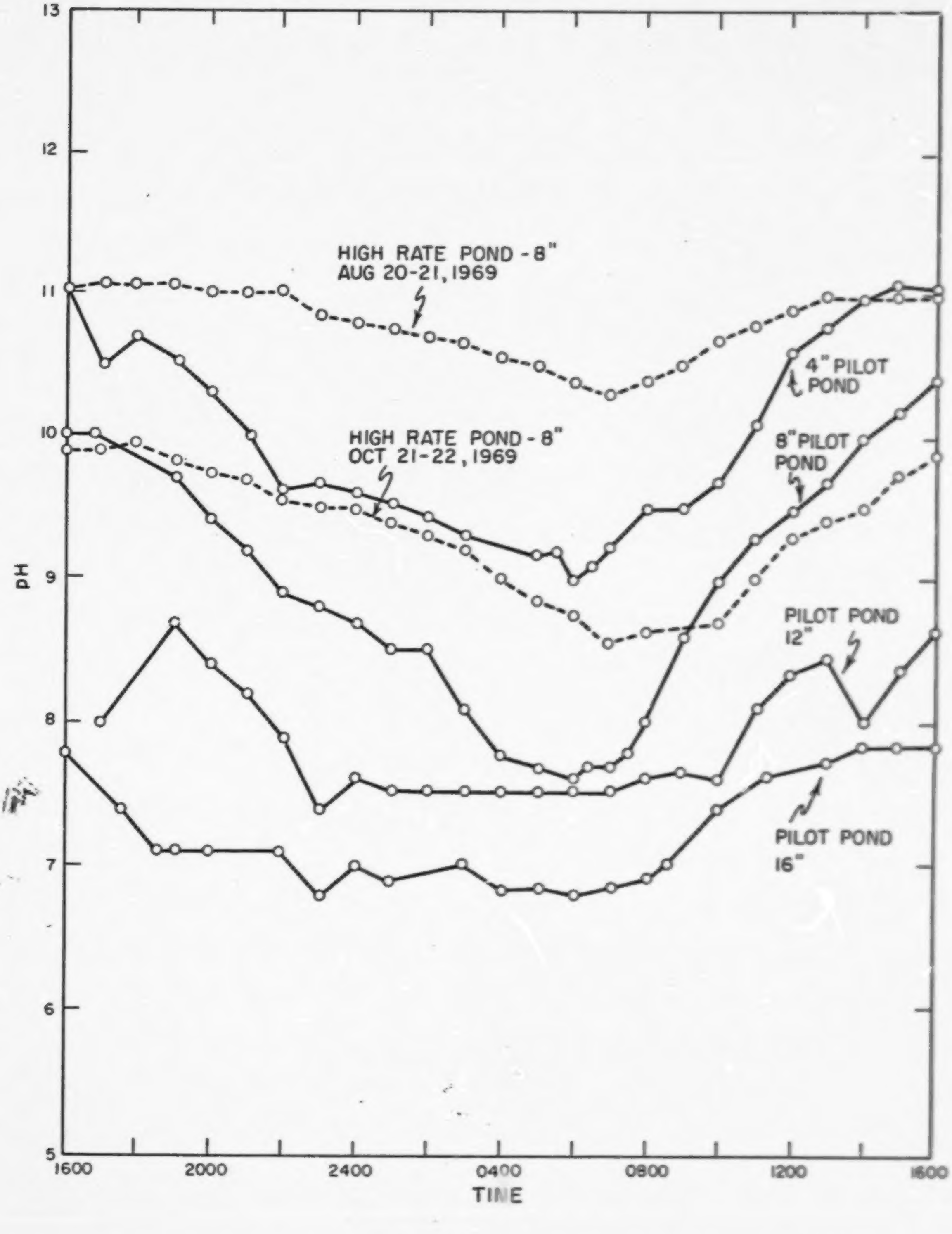

FIGURE 46- VARIATION IN pH WITH POND DEPTH AND TIME OF DAY

mentioned, the detention time in the Saint Helena pond system in winter and spring was 110 days. In the summer and fall, the system has no discharge, and, hence, the detention time becomes unlimited. In this large system, no sensitivity problems in regards to pH or other factors were observed.

To summarize and conclude the preceding discussion, laboratory findings in which pH control or mixing with air or air enriched with CO_2 cannot be directly translated into outdoor applications because a carbon deficiency and/or pH problems develop in outdoor pond unless provision is made for adding or conserving CO_2.

Results from small pilot plant ponds have to be evaluated carefully in light of their insufficient buffer capacity and sensitivity to rapid changes in pH.

Because of the large capacities characteristic of the Saint Helena stabilization pond system, the findings from this system indicate that it is the best application of the objective stabilization ponding set forth herein and the findings should be applicable to other stabilization pond systems.

Ammonia Losses

The mechanism by which nitrogen is lost from ponding systems is of great interest. Ammonia loss is perhaps one mechanism. In summer months when pond temperatures were above 20°C and pH levels above 9, either none or very low ammonia concentrations were found in the pond systems studied. The concentrations along with pH levels, and temperatures are listed in Table XLII, which clearly documents the existence of some ammonia loss mechanism.

As is well known, ammonia may exist in cationic form and in unionized gas form as indicated by the dissociation constant, i.e.,

TABLE XLII

AMMONIA LOSSES IN RELATION TO TEMPERATURE, pH, AND DETENTION TIME

Pond	Date	Temperature °C	pH	Detention Time-Days	Ammonia Concentration mg/liter*
Richmond	Aug 20 69	21.4	10.8	5.0	0.0
Saint Helena (Polishing I)	Aug 31 70	25.7	9.5	26.8	0.0
Saint Helena (Settling)	Aug 31 70	25.0	9.2	13.1	0.8
Richmond	Oct 21 69	17.8	9.3	5.0	4.6

*Typical influent concentrations of ammonia are 26.0 mg/liter for Richmond and 25.6 mg/liter for Saint Helena.

$$\frac{[NH_4^+] \quad [OH^-]}{[NH_3]} = K_b = 1.71 + 10^{-5} \text{ at } 20^{\circ}C \quad \text{Ref (100)}$$

According to Figure 13, at a pH of approximately 9.6 (20°C) the distribution is about equal between the un-ionized gas, and the cationic species. As can be seen from the position of the pH values for the various sampling points in the figure, one would expect the two Richmond samples in August and the two Saint Helena samples to have low ammonia concentrations as indeed they did.

Stratton (121) states that the un-ionized ammonia gas species may be removed from natural water in significant quantities by natural degasification processes, even when the pH is as low as 8.5.

Considering the other possible losses of ammonia, i.e., nitrification followed by denitrification, the loss may take the form:

$$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \rightarrow N_2 \quad .$$

In general, the conditions in stabilization pond systems do not lend themselves to conditions under which ammonia is first oxizided to NO_3^- and later denitrified under anaerobic conditions. In fact, the opposite may be observed in pond systems. Thus, in the Saint Helena system, the first pond is anaerobic, and in the summer is anaerobic almost up to the surface. However, in the units following the anaerobic pond, aerobic conditions predominate, and thus the anaerobiosis needed for denitrification do not exist, at least to a significant extent.

In activated sludge plants anaerobic denitrification is actually emplyed to eliminate nitrogen. In agriculture, waste waters having high NO_3^- concentrations (e.g., the Firebaugh project), denitrification is especially designed to be accomplished by anaerobic ponding, and provision is made to guard against diffusion of atmospheric O_2 into the ponds.

However, significant denitrification seems to be only remotely probable in the thin algal-sludge layers at the bottom of the settling and polishing ponds of the Saint Helena system, even though pockets of anaerobic particles may occur.

Some N_2 release from the anaerobic pond in Saint Helena is possible, but because of the minute concentrations of nitrates found in the remaining Saint Helena ponds, release of N_2 in those ponds appears to be only a remote possibility.

Conditions for ammonia losses through natural degasification in rivers (121) as described by Stratton, as well as the losses from the Richmond high-rate ponds which could not be accounted for by Golueke, *et al.* (96) other than by volatilization of ammonia are similar to those found in this study at the high-rate pond in Richmond (summer run) and Saint Helena (summer sampling program). In summary, therefore, it may be safely concluded that the nitrogen loss observed in the study was by way of volatilization of ammonia from the pond. Uptake of ammonia by algae, followed by sedimentation of the algae is a distinct possibility. If ammonia is assumed to be the major source of nitrogen for algae and if algae are assumed to be 8% nitrogen, one may obtain an estimate of algal concentrates. For example, in Saint Helena, the ammonia concentration entering the algal pond at one time was 7.0 mg per liter and the corresponding algal concentration would be $7/0.8 = 87.5$ mg per liter. Algal concentrations of this magnitude were not attained, the maximum being about 83 mg per liter and the mean 53.4 mg per liter. Thus, significant quantities of ammonia were probably taken up by algae.

Aesthetic Values

Sewage treatment plants should be nuisance-free and should blend into the environment without deterioration of aesthetic values. This concept cannot be easily accomplished with conventional treatment facilities. Many times the brightly painted digesters and/or other treatment facilities on the outskirts of suburban or rural communities have an opposite effect. On the other hand, stabilization pond systems do not need large treatment structures which may deteriorate aesthetic values. The Saint Helena pond system, for example, has only a small control building. The other visible evidence of the pond system is the dikes which blend well into the agricultural environment.

ALGAE AS AGENTS FOR NUTRIENT REMOVAL

In the course of the study it was found that in addition to light limitations two major conditions restricted in varying degrees the removal of nutrients. The two conditions were 1) imbalance of nutrients with the result that the algae could not incorporate sufficient amounts of nitrogen and phosphate into the cell material, and 2) the appearance of daphnia in polishing ponds, which lead released nitrogen from dead algae as well as a drop in algal production, and therefore adverse uptake of nutrients by algae.

Nutrient Balance

Nutrient uptake by algae from wastewater is believed to be strongly influenced by the relationship between nutritional needs of the algae and the composition or nutrient content of the waste involved. It is further presented that removal efficiency of the major nutrients--carbon, nitrogen and phosphorus--is influenced by the ratio of these same three major nutrients. A correlation of this hypothesis is that other factors being equal the performance of ponding systems can be predicted on the basis of these ratios.

Based on data from various sources, the ranges of the three major nutrients, namely, carbon, nitrogen, and phosphate, in the composition of algae (on a dry weight basis) are summarized in Table V, cf. page 31.

In order to compare the performance of the various systems using this hypothesis, it is necessary to know the input-output concentrations of nutrients for the various steps of the systems.

The main difficulty of examining data on waste water composition is that generally carbonaceous matter is only measured as BOD or COD, but not as T-C (total carbon). In this study, however, carbon measurements were emphasized, and as a result, data on carbon concentration on raw sewage are available. These data, together with data from other sources, are summarized in Table XLIII. A comparison of data in this table to that of Table V indicates that the carbon concentrations in raw sewage are not sufficient to support a concentration of algae and/or to remove effective nitrogen and phosphate biologically.

Because of the nutrient imbalance in raw sewage and in the subsequent pond liquids, nutrient removal in stabilization ponds is only partly successful. In this light it is worthwhile to reexamine the influence of the nutrient balance and the nutrient ratios regarding the differences in nutrient removal efficiencies between the Concord pond system and the Saint Helena pond system.

At the Concord pond system in which nutrient removal was found to be poor, the following situation exists: the raw sewage C/N ratio originally 5.17 is reduced in conventional treatment processes by elimination of carbon without proportional elimination of nitrogen. In the absence of a carbon input, this situation does not improve in the following pond system. Consequently, the C/N ratio at the polishing pond influent (see Table XLI) is 2.42 and at the effluent, 2.72. As might be expected, lightbox studies with pond liquid from this polishing pond in which nutrient ratios were adjusted with carbon, indicated an increase in algal growth and a proportional increase in nitrogen removal.

In the Saint Helena pond system, which exhibited effective nutrient removal efficiencies, the raw sewage has a C/N ratio of 3.71, but due to loss of nitrogen, this ratio increases in the pond system and reaches a ratio of 6.96 at the influent of polishing pond II. The C/N ratio at the effluent of this polishing pond II is 9.03. Light-box studies with this pond liquid, adjusted with carbon and nitrogen, did not indicate any specific increase in algal growth and related nutrient removal indicating possibly that some elements other than C or N were involved.

There seem to be two major reasons for this improvement in nutrient removal and nutrient ratios in the Saint Helena pond system: 1) The effective sedimentation and loss of nitrogen brought about an adjustment of nutrient ratios in the deep anaerobic pond (influent C/N is 3.71 and effluent C/N is 6.10 (see Table XLI), and 2) Because of long detention times and because of the large water surface areas exposed to the atmosphere, there is the opportunity for large-scale gas exchange.

If lined high-rate ponds are operated at shallow depths so that light is not limiting and under controlled conditions including proper mixing, pH ranges and controlled carbon supply (as CO_2), removal of nitrogen and phosphorus by photosynthetic stripping should be possible. For nitrogen removal, the amount of carbon required to satisfy the carbon deficiency does not seem large. However, according to the ratios shown, an inordinately large carbon supply would be required to attain complete phosphate removal.

TABLE XLIV

BOD, COD, AND T-C LEVELS FOR RAW SEWAGE

Location	COD	Levels in mg/l BOD	T-C	Ratios COD/BOD	BOD/T-C	COD/T-C
Richmond	318.0	177.0	135.0	1.79	1.31	2.37
Concord	344.0	178.0	160.0	1.93	1.11	2.15
St. Helena	307.0	142.5	131.5	2.15	1.08	2.33
Mean	323.00	165.8	142.2	1.96	1.17	2.28
Standard Deviation	19.0	20.2	15.5	0.182	0.125	0.117
Coefficient Variations	5.9%	12.2%	10.9%	9.3%	10.7%	5.1%

In order to have a better understanding of the various fractions of carbon which were analyzed and of this relation to the BOD test, some of the results from the Saint Helena pond study are reviewed.

As previously described, detailed analyses made of samples from the Saint Helena pond system (BOD, COD, and T-C tests - See Table XLIV) revealed the following facts:

1) The organic carbon in the solid fraction (indicative of the BOD as shown in Figure 43) had its last positive value of 3.4 mg/liter at sampling point 4, and reached zero at sampling point 5 or before. These two values (3.4 mg/liter and 0.0 mg/liter) indicate that the treatment process, as far as BOD was concerned, terminated at sampling point 4 (detention of 41.9 days or 38.9% of the total detention time), and a very small amount of BOD was applied to the following two polishing ponds.

2) The reduction of carbon in the dissolved organic fraction form was only 62.0%, as compared to a 97.2% reduction of BOD. Therefore, dissolved organic carbon concentrations of 5.5 mg/liter could still be found after 110 days of detention time at sampling point 6 (see Table XXIV). As already mentioned, this dissolved organic fraction is not detectable by the BOD test and its composition is unknown. In the COD test, one can detect portions of the dissolved organic fraction. This is indicated by a 21.6 mg/liter level of COD at sampling point 6 (see Table XXIII). However, the most precise test which can distinguish between the dissolved inorganic carbon fraction and the dissolved organic carbon fraction is the T-C test.

The dissolved organic fraction of carbon may include non-degradable residues not used by microorganisms, excreted algal shunt materials, pesticides and other compounds. These compounds are organic pollutants which may cause odor, color, and taste problems in the receiving waters. If the receiving waters are reused, the detection of such organic pollutants is of great importance, and the T-C test is, therefore, a worthwhile analytical tool in the field of water reclamation.

3) The remaining inorganic carbon fraction (also detectable by the T-C test) is the carbon portion of alkalinity which has the same reduction pattern (percentage wise) as alkalinity throughout the entire pond system. This pattern can be followed in Figure 44.

4) As seen from Table XXIV, there is not any detectable solids fraction of carbon at sampling point 6, and the final carbon composition at this sampling point 6 is, therefore, 21.6 mg/liter dissolved inorganic, and 5.5 mg/liter dissolved organic carbon.

Considering the different fractions of carbon and their detectability throughout pond systems, the following may be concluded:

The T-C test is not only an important test in the water pollution and reclamation field, and is also important in the design of treatment processes in which nutrient balances must be determined or predicted. The COD test is also important in the water pollution control field with special application for industrial wastes. However, the BOD test is the only test which indicates the quantity of oxygen that will be utilized by natural agents (microorganisms) in stabilizing organic matter in the primary units of a stabilization pond system. Therefore, the BOD test continues to be an important test in water quality management, at least as far as treatment by ponding is concerned.

DESIGN AND OPERATION OF STABILIZATION POND SYSTEMS

Considering the foregoing results, it is worthwhile at this point to outline certain desirable design characteristics for ponds.

Recommended Disgin Criteria for Stabilization Pond Systems (Saint Helena Type)

1) Anaerobic Ponds - Loadings should not be higher than 250 lb/acre/day, so as to keep an effective dissolved oxygen layer preventing nuisance conditions on top of the anaerobic pond liquid.

2) Unlined High-Rate Ponds - a) Detention times should not exceed three to four days; b) operations should be carried out at pumping rates as designed (0.50 ft/sec); c) provision should be made to reverse the pumping direction to accomplish better mixing; d) provision for possible CO_2 injection should be made; e) provision for removal of inorganic sludge accumulations are needed.

3) Algal Growth and Settling Pond - In the design of future stabilization pond system layouts, consideration should be made to incorporate a shallow autoflocculation pond four to six inches deep. Such a shallow autoflocculation should precede the algal settling pond. Provision for the addition of chemicals and for removal of the algae should also be made.

Operation Parameters for Lined High-Rate Ponds

1) Lined high-rate ponds need regular supervision and control. An uninterrupted sewage supply of constant strength is also very important.

2) To operate lined high-rate ponds efficiently for nitrogen conservation and removal, addition of carbon as CO_2 gas or bicarbonate for nutrient and pH control is necessary.

3) Adjustment of the pond depth in accordance to season, i.e., less depth in winter and greater depth in summer should be considered.

4) The time of mixing should be adjusted in accordance with season; and night mixing in winter and daytime mixing in summer should be explored.

Analysis for Stabilization Ponds

As previously mentioned, one of the aims of this study was to find relatively simple analyses which could be carried out by a plant operator in field laboratories.

Two such analyses have been selected and are described at this time:

1) Daily pH measurement such as those used for digesters. This is a simple measure which does not consume a great deal of time. It indicates in one single reading the general behavior and conditions of a pond. If, for example, the pH reaches the critical 10.0 to 10.5 level, corrective measures should be taken to lower the pH. The time when such pH readings should be made will have to be specified.

2) Occasionally, a simple nutrient deficiency analysis should be made. This analysis would consist of filling five flasks with 200 ml of pond water and adding bicarbonate to the first flask, ammonia to the second flask, phosphate to the third, and iron in the fourth flask. The fifth flask serves as a control. These flasks should be placed for approximately one week on a north window sill away from direct sunlight and algal growth patterns should be observed daily. If, due to the results of this test, nutrient addition is found necessary to attain algal growth, the appropriate nutrient (in the least expensive form) should be added to the pond liquid in accordance with the findings of the analysis.

   Such a flask experiment was carried out successfully in the Saint Helena study (described in Chapter IV) and the results were very helpful in discerning nutrient requirements.

Need for Future Research

In the course of the study, many still unanswered questions arose and the need for additional research in certain areas of stabilization pond design and operation became apparent. The most important are:

1) Gas exchange - This is a field where much basic information is lacking. It is especially important for shallow ponds with a great surface area in relation to pond volume. The gas exchange behavior of important gases such as oxygen, ammonia, and carbon dioxide should be investigated first.
2) Composition and function of pond bottom sludges - Research in this almost unknown field will help to explain the successful operation of the unlined high-rate ponds and the pH stability of these ponds. Such research should also include investigation on the release of organic acid end-products through bacterial breakdown activity in order to counter-balance hydroxide formation at the alkalinity shift. Another investigation pertaining to bottom sludge would be a feasibility study of continuous sludge removal from lined high-rate ponds.
3) The possibility of using shallow ponds with high pH levels for the removal of ammonia as gas, and phosphate as precipitate, should be investigated on a pilot plant scale.
4) The whole concept of polishing ponds should be studied. The problems with these ponds are related to their low efficiencies versus the large areas which they occupy. The possibility of other means of "polishing", such as gravel beds with growing vegetation should be investigated.
5) Phase isolation, whereby a separate bacterial unit (enclosed and operated like a digester) and a separate algal unit are operated in series, should be investigated on a pilot plant scale.

6) The conditions under which algae grow in stabilization pond systems should be investigated. Conditions to be evaluated are: 1) algal growth under favorable light conditions, 2) algal growth under dim light conditions, and 3) algal growth in deeper layers without light.

VI. CONCLUSIONS

Stabilization pond systems can be successfully used to treat sewage under changing outdoor conditions to the degree necessary to meet specified water quality standards. Although such pond systems operate under uncontrollable light, temperature, and to a great extent uncontrollable nutrient supply conditions, design and operation parameters may be used to help overcome the variable outdoor conditions. These parameters are depth of pond, loading, mixing, nutrient balance, and pH control.

Three treatment objectives can be achieved in stabilization pond systems and expecially in high-rate ponds; namely, BOD removal, nutrient removal, and algal production. However, design criteria and operation procedures of the ponds have to be adjusted on the basis of which of the three treatment objectives are to be accomplished.

If BOD removal is the treatment objective, a deep anaerobic pond, followed by an unlined high-rate pond, and a final settling pond seems to be a satisfactory solution. If nutrient removal is the objective, the deep anaerobic pond should be followed by a lined high-rate pond. In order to control the pH, and to achieve nutrient balance, the introduction of CO_2 gas may be necessary. The lined high-rate pond should be followed by a shallow pond for final treatment. In such a shallow pond, pH levels will have to be raised (with or without chemicals) for final removal of phosphates (by precipitation), and of ammonia (by volatilization or fixation in algae). Chemical flocculation for final treatment may also be a part of such a pond system.

If algal growth is the objective, the anaerobic unit should be enclosed and operated as a digester from which the liquified solids are supplied to a lined high-rate pond which follows. In the lined high-rate pond, pond depth, mixing, nutrient balance, and pH will have to be strictly controlled. The removal of algae from the pond liquid should be accomplished by centrifuges and/or other suitable economical methods of harvesting.

Design and operation parameters for the shallow pond (for final treatment), and for the enclosed anaerobic unit will have to be established by way of future outdoor pilot plant studies. In addition, continuous operational control of the lined high-rate pond will be an essential part of an algal growth and nutrient removal pond system.

Additional findings made in the study which may be helpful in the design and operation of stabilization ponds are:

1) To avoid objectionable odors, loadings to deep anaerobic ponds should not exceed 250 lb/acre/day. This is the maximum loading at which an effective concentration of dissolved oxygen can be maintained in the top layer of an anaerobic sludge on a sustained basis. (The top layer should be aerobic so as to permit the oxidation of odorous reduced compounds.)
2) The BOD test was found to be a meaningful test for the first pond units in a stabilization pond system. However, the BOD test is less meaningful in evaluating the performance of polishing ponds.
3) Deep inlet structures and a build-up of sludge solids were found to be important for the proper functioning and performance of anaerobic ponds.
4) In high-rate ponds, not equipped for CO_2 injection, a certain amount of sludge deposition may be helpful for pH control.
5) Algae are effective agents for nutrient removal provided the nutrients in question are available in balanced quantities. Nutrient ratios are helpful in detecting the needed nutrient balanced.

6) The results also confirm the concept that these biological unit processes are greatly influenced in performance by the nutritional quality of wastes and, hence, by their position in a series of processes.

7) To better control the performance of stabilization pond systems, a daily pH measurement and a periodic nutrient analysis should be made.

VII. SUMMARY

From the beginning of this century, mechanical sewage treatment processes now recognized as "conventional" developed rapidly in the U.S.A. and in Europe. The processes involved reflected the high degree of industrialization of these countries. Stabilization ponds as intentionally designed treatment systems appeared in the early 1940's in the U.S.A. and have slowly gained acceptance. In developing counties, however, stabilization ponds were more rapidly accepted.

At the time when waste stabilization ponds were first developed and studied, BOD and coliform MPN were the primary parameters by which treatment performance could be satisfactorily evaluated. However, now that stabilization pond effluents are being destined for utilization in agriculture, industry, and ground water recharge, there is a need for additional parameters to reflect the additional degrees of treatment required in various applications.

Fundamental relationships of complex algal-bacterial ecology in stabilization ponds have been under study for about 20 years at the University of California, Algal Research Laboratory, Richmond, California and elsewhere. Based on fundamental information gained from these studies, stabilization pond systems in the San Francisco Bay Region have been designed and constructed. Three of the systems, namely those in Richmond, Concord, and Saint Helena have been investigated in the study reported herein.

The research work began with a review of previous publications followed by studies at the Richmond Field Station pilot ponds and later extended to field tests at the stabilization pond systems at Concord and

Saint Helena. These field tests were supplemented by laboratory studies of nutrition addition involving the use of flask cultures maintained in light boxes.

The five treatment steps for sewage, cf. page 11, can be accomplished in the order outlined by conventional-mechanical treatment processes by stabilization pond systems, or by specially designed ponds such as those used for salt concentration.

In stabilization pond systems, the progressive increase in waste purification from one pond to another is clearly indicated by changes in micro- and macroorganisms in a stabilization pond system. Phases in the system are: 1) the bacterial phase; 2) the algal phase; and 3) the grazing or predator phase.

Light and temperature are of paramount importance in the operation and performance of stabilization pond systems. They affect photosynthesis, oxygen production, and many other biological and chemical reactions. Photosynthesis is a complex process involving light-sensitive and temperature-sensitive processes. For example, the splitting of water in photosynthesis is a light-sensitive reaction, whereas the reduction of carbon dioxide is controlled by enzymes and is temperature sensitive.

Solubility of gases, gas exchange, and pH level are also important environmental factors, but these factors are partly controlled by microbial activities which change pH levels and therefore the solubility of gases and finally the gas exchange itself.

The compositions of algae and bacteria are similar; namely, approximately 53% carbon, 7% hydrogen, 30% oxygen, 9% nitrogen, and 1% phosphorus. Based on these percentages of composition, the C/N and C/P ratios are 6.0 and 53.0 respectively. Basic nutrient requirements and nutrient ratios based on these ratios are extensively used as parameters in many other fields such as agricultural plant nutrition, in composting, and in the activated sludge process, and, hence, should also apply to oxygen production and nutrient uptake by algae.

The modified Mitscherlich limiting factor equation by Verduin is:

$$Y = Y\ \text{opt.}\ (1 - 2^{-x})\ (1 - 2^{-y})\ (1 - 2^{-z})\ (\underline{\qquad})(\underline{\qquad})\ \text{etc.}$$

where Y is the photosynthetic yield, Y opt. is the yield obtained if all factors are present at optimal intensity, and x, y, and z are the factors influencing the photosynthetic process. Such an equation seems to have advantages over the single limiting factor type of equation set forth by Michaelis-Menten especially when used in natural outdoor conditions.

The 145 W Melbourne system in Australia consists of eight ponds in series with a total detention time of 38.5 days. The first two ponds are anaerobic, the third and fourth ponds are algal ponds and the last four ponds are polishing ponds. The overall BOD reduction was very good, from 521.0 to 10.6 mg per liter. However, the total nitrogen showed an increase from 58.7 to 67.0 mg per liter in the first two ponds and decreased thereafter to a 27.9 mg per liter concentration in the effluent.

The Herzliya stabilization pond system in Israel consists of four ponds in series, with a total detention time of 26.0 days. As in the Melbourne system, BOD reduction was satisfactory (from 285.0 to 37.0 mg per liter), but total nitrogen and total phosphorus reduction was less effective. These reductions were from 76.4 to 47.1 mg per liter for total nitrogen and from 10.4 to 8.3 mg per liter for total phosphorus.

Composite samples were taken for raw sewage analyses, and grab samples for pond liquids. For depth profile samples, a special submersible sampling device was constructed.

Appropriate methods of analysis were selected from the "Standard

Methods," the SERL Methods, and the AOAC methods for quantitative and qualitative determinations of the different constituents under investigation. For carbon analysis, however, the Beckmann Carbon Analyzer was employed.

The Richmond High-Rate Pond

The high-rate pond located at the Richmond Field Station is 80 feet wide, 334 feet long, and occupies 0.6 acre. The pond is lined and operates most of the year at an eight-inch depth. Four low-head pumps are used to mix the pond liquid and move it at a velocity of 1.0 ft per second.

Two 24-hour sampling runs were carried out. The first in August (summer) and the second in October (early fall). During these sampling runs, temperature, pH, alkalinity, hardness, as well as nitrogen and phosphates were analyzed.

Under the long daylight hours and the high temperatures prevailing at the time of the August run, a pond failure occurred. This failure was related to the high pH level and subsequent biological and chemical reactions described in detail in the section "Analyses of Pond Failure."

The sludge accumulation in the lined high-rate pond did not attach itself to the pond bottom. Because of this property and the relatively high inorganic (fixed) solids content of 57.3%, continuous sludge removal seems worthy of consideration.

The Concord Stabilization Pond System

The treatment works of the city of Concord include a conventional secondary treatment plant and a stabilization pond system. The stabilization pond system consists of two anaerobic units, an aerobic high-rate pond unit, and a high-rate polishing pond. The total acreage of this system is 20.7 acres and the detention time, based on a 4.6 MGD average daily flow, is 6.7 days.

From the analytical data presented, it is evident that the Concord stabilization pond system is effectively removing BOD in a short detention time. This pond system, however, fails in the removal of nitrogen and phosphate.

The reasons for this ineffective nutrient removal seem to be:

1) An imbalance in nutrient supply due to a dearth of carbon;
2) Excessively short detention time in most of the pond units;
3) A misplaced and, hence, ineffective anaerobic pond;
4) Insufficient light penetration in the high-rate pond.

Special attention was given to a bacterial sludge-slime layer which developed in the unlined high-rate pond. This attached sludge layer was found to have two important properties:

1) It protected the pond bottom from erosion
2) It released nutrients into the overlaying pond liquid.

The Saint Helena Stabilization Pond System

The Saint Helena pond system consists of five ponds--an anaerobic pond, a high-rate pond, a settling pond, and two polishing ponds. The total pond area is 19.5 acres and the detention time, based on a 0.418 MGD average daily flow, is 110 days.

Physical and chemical characteristics of the pond liquid were analyzed during the sampling program, but special attention was given to the algal population, the daphnia population, and the quantities and ratios of carbon, nitrogen, and phosphate.

The overall results which are summarized in Table XXXIV indicate that the treatment performance of the anaerobic pond was excellent and that those of the high-rate pond good. The performance of the settling pond was at reasonable levels; but the two polishing ponds performed poorly. The excellent performance of the anaerobic pond (actually this pond should be called a deep facultative pond) is especially noteworthy.

A well-established population of daphnia and related organisms was found grazing on algae in the two polishing ponds during the spring. Because of nutrients released by the daphnia during consumption and digestion of the algae population, released nutrients were found in the effluent.

The Concord pond system which follows a conventional trickling filter plant, did not perform as well as the Saint Helena pond system which treats raw sewage. The reasons for better performance of the Saint Helena pond system were found to be:

1) Greater removals of BOD and nutrients due to longer detention times and high availability of the organic matter for microbial decomposition.
2) Decreases in nitrogen in the deep anaerobic pond which brought the carbon-nitrogen ratio into a better nutritional balance for algae to grow in the following pond units.
3) The superior sunlight conditions during the Saint Helena sampling period (spring) than during the Concord sampling period (late fall).

Because of the protective sludge layer which was found to develop on the bottom of the unlined high-rate ponds studied, erosion and related turbidity was found to be minimized in these ponds. The absence of a sludge layer in the lined high-rate pond at Richmond indicated that it was nutritionally deprived due to low sewage flows. Nutritional deprivation in turn caused increases in pH which further hindered decomposition.

Sludge accumulation in all pond units of a stabilization pond system is one phase of the natural aging process of ponds. This aging process will undoubtedly influence pond operation in the long run.

Two factors restrict nutrient removal in stabilization ponds; the first is related to the imbalance of nutrients in sewage marked by a dearth of carbon, excess nitrogen and a great excess of phosphate; and the second is the growth of daphnia (algae feeders) or other higher organisms which feed on algae and release their nutrients in soluble forms.

A need for additional research in certain areas of stabilization pond design, function, and operation became apparent in this study. The most important areas for study appear to be: 1) gas exchange, 2) composition and function of bottom sludge, 3) the possibility of using shallow ponds for nutrient removal, and 4) the whole concept of polishing ponds.

A periodic nutrient substitution analysis in the laboratory and daily pH measurement should aid in the decision of stabilization pond operation and control.

APPENDIX

TABLE A-1

pH Levels and Temperature Readings in the August 20-21, 1969 Sampling Run

Time	pH	Temperature (°C)
0900	10.50	17.5
1000	10.70	17.8
1100	10.80	19.0
1200	10.90	20.8
1300	11.00	22.8
1400	11.00	24.6
1500	11.00	25.8
1600	11.00	26.5
1700	11.05	26.5
1800	11.05	26.0
1900	11.05	25.0
2000	11.00	24.0
2100	11.00	23.0
2200	11.00	22.0
2300	10.85	21.1
2400	10.80	20.4
0100	10.75	20.5
0200	10.70	19.5
0300	10.65	19.0
0400	10.55	19.0
0500	10.50	18.5
0600	10.40	18.0
0700	10.30	18.0
0800	10.40	17.8
Mean	10.79	21.38

TABLE A-2

Calcium, Magnesium, Total Hardness, Ammonia, and Phosphate Concentrations in the August 20-21, 1969 Sampling Run
(all Values in mg/1)

Time	Calcium (as $CaCO_3$)	Magnesium (as $CaCO_3$)	Total Hardness (as $CaCO_3$)	Ammonia-N	Phosphate (PO_4)
0900	33.4	48.0	81.4	0.00	3.18
1000	33.4	41.6	75.0		2.85
1100	32.6	48.9	81.5		2.62
1200	31.4	43.6	75.0		2.43
1300	30.8	32.2	63.0		2.24
1400	30.0	33.0	63.0		2.15
1500	29.2	31.8	61.0		1.99
1600	28.6	31.4	60.0		1.97
1700	30.0	30.0	60.0		2.02
1800	30.0	30.0	60.0		2.13
1900	33.4	24.6	58.0	All Values	2.11
2000	34.0	20.5	54.5		2.12
2100	34.0	20.5	54.5		2.02
2200	33.4	17.6	51.0		2.18
2300	33.4	21.1	54.5		2.24
2400	32.6	25.4	58.0		2.19
0100	35.4	35.6	61.0		2.45
0200	32.2	35.8	68.0		2.45
0300	33.4	38.1	71.5		2.45
0400	32.6	43.9	78.5		2.68
0500	32.2	42.8	75.0		2.67
0600	32.2	48.3	80.5		2.85
0700	30.0	50.5	88.5		2.75
0800	30.0	40.0	77.0	0.00	2.91
Mean	32.01	34.80	67.10		2.40

TABLE A-3

Total Alkalinity, H_2CO_3, HCO_3^-, $CO_3^=$, OH^-, and Inorganic Carbon in the August 20-21, 1969 Sampling Run
(all values in mg/1)

Time	T-Alkalinity (as $CaCO_3$)	H_2CO_3 (as $CaCO_3$)	HCO_3^- (as $CaCO_3$)	$CO_3^=$ (as $CaCO_3$)	OH^- (as $CaCO_3$)	Inorganic Carbon
0900	67.0	0.0	12.8	43.2	11.0	9.3
1000	75.2		8.9	48.4	17.9	7.6
1100	85.2		7.5	52.7	24.9	6.6
1200	91.9		5.4	50.2	36.3	6.2
1300	103.2		3.8	45.8	53.6	5.2
1400	103.4		3.1	38.7	61.7	5.4
1500	106.5		2.8	36.0	67.6	4.6
1600	110.5		2.8	36.3	71.3	4.3
1700	98.9	All Values	2.0	25.6	71.3	5.1
1800	102.2		1.6	23.6	77.1	4.9
1900	99.9		2.6	33.6	63.6	5.3
2000	103.1		3.3	40.9	58.9	4.6
2100	88.4		2.6	31.6	54.4	5.0
2200	78.1		2.2	25.7	50.3	6.2
2300	78.9		4.9	40.8	33.1	6.3
2400	73.8		5.6	40.6	27.6	6.6
0100	75.0		6.7	43.2	25.1	6.0
0200	73.4		8.0	44.8	20.6	6.8
0300	63.1		7.6	37.8	17.6	7.4
0400	61.4		9.6	37.8	14.0	7.5
0500	64.1		11.7	40.5	12.0	8.3
0600	62.9		14.5	39.4	9.1	8.9
0700	63.5		17.8	38.5	7.3	8.0
0800	66.4	0.0	15.5	41.9	9.0	9.7
Mean	83.2		6.8	39.1	37.3	6.61

TABLE A-4

pH Levels and Temperature Readings in the October 21-22, 1969 Sampling Run

Time	pH	Temperature °C
0900	8.08	13.4
1000	8.70	15.0
1100	8.98	17.6
1200	9.31	20.0
1300	9.37	21.8
1400	9.51	23.0
1500	9.74	23.0
1600	9.88	23.0
1700	9.92	21.9
1800	9.95	20.8
1900	9.86	19.3
2000	9.75	18.5
2100	9.67	17.7
2200	9.55	17.1
2300	9.51	16.1
2400	9.50	16.0
0100	9.38	15.9
0200	9.30	15.8
0300	9.20	15.5
0400	9.00	15.2
0500	8.85	15.2
0600	8.75	15.0
0700	8.55	15.2
0800	8.65	15.5
Mean	9.29	17.80

TABLE A-5

Total Alkalinity, H_2CO_3, HCO_3^-, $CO_3^=$, and OH^- in
the October 21-22, 1969 Sampling Run
(all values in mg/l)

Time	T-Alkalinity (as $CaCO_3$)	H_2CO_3 (as $CaCO_3$)	HCO_3^- (as $CaCO_3$)	$CO_3^=$ (as $CaCO_3$)	OH^- (as $CaCO_3$)
0900	165.8	2.9	163.9	1.9	0.0
1000	164.6	0.7	156.6	7.9	0.1
1100	164.1	0.3	148.5	15.2	0.3
1200	162.4	0.1	131.1	30.4	0.9
1300	159.8	0.1	124.1	34.5	1.2
1400	156.3	0.1	110.9	43.7	1.8
1500	153.8	0.0	90.4	60.5	3.0
1600	147.7	0.0	74.6	68.9	4.1
1700	146.7	0.0	71.7	70.9	4.2
1800	150.6	0.0	72.1	74.4	4.1
1900	150.6	0.0	81.6	66.1	2.9
2000	149.0	0.0	90.8	56.0	2.1
2100	148.3	0.0	97.5	49.1	1.7
2200	148.1	0.1	106.8	40.2	1.2
2300	148.7	0.1	110.7	37.0	1.0
2400	148.7	0.1	111.4	36.3	1.0
0100	149.6	0.1	125.9	23.0	0.7
0200	150.9	0.1	124.8	25.5	0.6
0300	151.3	0.2	129.9	20.9	0.5
0400	154.9	0.3	140.4	14.2	0.3
0500	155.4	0.4	144.8	10.4	0.2
0600	154.5	0.5	146.0	8.3	0.2
0700	157.3	0.9	151.8	5.4	0.1
0800	157.6	0.7	150.6	6.8	0.1
Mean	154.3	0.3	119.0	33.7	1.3

TABLE A-6

Calcium, Magnesium and Total Hardness Concentrations in October 21-22 Sampling Run (all values in mg/1)

Time	Calcium (as $CaCO_3$)	Magnesium (as $CaCO_3$)	T-Hardness (as $CaCO_3$)
0800	79.5	--	--
0900	59.8	34.6	94.4
1000	64.4	30.3	94.7
1100	60.3	23.0	83.3
1200	63.5	18.1	81.6
1300	59.5	27.6	87.1
1400	54.9	31.1	86.0
1500	54.4	26.4	80.8
1600	47.3	31.9	79.2
1700	44.9	33.8	78.7
1800	56.2	23.3	79.5
1900	54.9	22.4	77.3
2000	53.8	26.4	80.2
2100	60.0	20.3	80.3
2200	49.2	32.7	81.9
2300	55.2	25.4	80.6
2400	53.0	29.5	82.5
0100	57.0	22.4	79.5
0200	57.9	27.1	85.0
0300	55.4	30.0	85.4
0400	55.0	30.0	84.9
0500	54.6	32.7	87.3
0600	54.1	28.7	82.8
0700	53.5	34.9	88.4
0800	54.1	33.5	87.6
Mean	56.5	28.17	83.88

TABLE A-7

Total Carbon, Total Nitrogen, Ammonia and Phosphate Concentrations in the October 21-22, 1969 Run

Time	Carbon (total, mg/1)	Nitrogen		Phosphate (PO_4) (mg/1)
		Total (mg/1)	Ammonia (mg/1)	
0800	53.0	8.4	7.2	10.7
0900	56.0	8.7	6.8	10.6
1000	58.0	7.7	6.5	9.1
1100	54.0	8.9	5.6	8.4
1200	57.0	8.9	5.2	8.9
1300	54.0	8.5	5.6	8.2
1400	57.0	7.9	4.8	6.7
1500	59.0	7.8	4.7	--
1600	54.0	7.4	4.4	5.5
1700	53.0	6.4	3.9	4.8
1800	59.0	4.5	3.9	5.2
1900	50.0	5.7	3.8	4.4
2000	50.0	5.7	4.0	4.4
2100	45.0	6.0	4.0	4.3
2200	60.0	5.9	3.7	6.1
2300	42.0	5.5	4.2	5.7
2400	50.0	6.4	3.9	4.9
0100	45.0	5.9	4.1	5.9
0200	41.0	6.7	4.1	7.1
0300	41.0	5.3	4.0	6.3
0400	40.0	6.5	4.0	7.1
0500	42.0	5.4	4.2	8.4
0600	42.0	4.5	3.8	7.5
0700	45.0	5.2	4.2	8.2
0800	45.0	5.1	4.1	7.1
Mean	50.08	6.50	4.59	6.90

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11.20.51.R7047CH OUTPUT
                        TABLE 8-A
          TABULAR EVALUTATION OF ALKALINITY DATA

          FOR ALGAE POND


         TEMP    TDS     PH      H2CO3    HCO3     CO3      OH  BUFFER CAPACITY


0900.    13.4   400.0   8.080     2.9    163.9     1.9      .0 -.201E-03
1000.    15.0   400.0   8.700      .7    156.6     7.9      .1 -.216E-03
1100.    17.6   400.0   8.980      .3    148.5    15.2      .3 -.352E-03
1200.    20.0   400.0   9.310      .1    131.1    30.4      .9 -.614E-03
1300.    21.8   400.0   9.370      .1    124.1    34.5     1.2 -.676E-03
1400.    23.0   400.0   9.510      .1    110.9    43.7     1.8 -.794E-03
1500.    23.0   400.0   9.740      .0     90.4    60.5     3.0 -.944E-03
1600.    23.0   400.0   9.880      .0     74.6    68.9     4.1 -.968E-03
1700.    21.9   400.0   9.920      .0     71.7    70.9     4.2 -.963E-03
1800.    20.8   400.0   9.950      .0     72.1    74.4     4.1 -.981E-03
1900.    19.3   400.0   9.860      .0     81.6    66.1     2.9 -.944E-03
2000.    18.5   400.0   9.750      .0     90.8    56.0     2.1 -.877E-03
2100.    17.7   400.0   9.670      .0     97.5    49.1     1.7 -.817E-03
2200.    17.1   400.0   9.550      .1    106.8    40.2     1.2 -.723E-03
2300.    16.1   400.0   9.510      .1    110.7    37.0     1.0 -.683E-03
2400.    16.0   400.0   9.500      .1    111.4    36.3     1.0 -.674E-03
0100.    15.9     0.    9.380      .1    125.9    23.0      .7 -.484E-03
0200.    15.8   400.0   9.300      .1    124.8    25.5      .6 -.522E-03
0300.    15.5   400.0   9.200      .2    129.9    20.9      .5 -.447E-03
0400.    15.2   400.0   9.000      .3    140.4    14.2      .3 -.327E-03
0500.    15.2   400.0   8.850      .4    144.8    10.4      .2 -.257E-03
0600.    15.2   400.0   8.750      .5    146.0     8.3      .2 -.219E-03
0700.    15.2   400.0   8.550      .9    151.8     5.4      .1 -.175E-03
0800.    15.5   400.0   8.650      .7    150.6     6.8      .1 -.196E-03


        KEY - - -

TEMP = CENTIGRADE
TDS = MG/L OF TOTAL DISSOLVED SOLIDS
H2CO3 = MG/L AS CO2
HCO3, CO3, & OH = MG/L AS CACO3
BUFFER CAPACITY =(DSUMCO2/DPH)-1
```

$$= \frac{\partial pH}{\partial \Sigma CO_2}$$

```
17

08/26/70  CAL SCOPE 3.1/2.5X VER.96.6PM  08/26/70 MACHINE A
11.20.34.HYDRA-    29 LINES ON MX103
11.20.34.R7047CH AT CP NUM 5.
11.20.34.CM= 8192/ 20000B AT CP=     0, PP=    0
11.20.34.R7047,,2,20000. TRUSSELL
11.20.34.CM=     /    000B AT CP=    0, PP=    0
11.20.34.COMMON,EVAL,SC.
11.20.35.LDCTL,NOMAP.
11.20.35.LGO,EVAL.
11.20.35.CM= 8192/ 20000B AT CP=     0, PP=    0
11.20.42.CM= 4352/ 10400B AT CP=     0, PP=    6
11.20.42.  BEGIN EXECUTION      TEST
   20.42.  STOP        TEST
```

TABLE B-1

Pond Liquid Temperature Readings (°C)

Date 1969	Samplint Point				Depth Profile at Sampling Pt. 3A Sampling Depth (feet)			
	2	3	4	5	Surface	1.0	2.0	3.0
10-23								
10-30	22.0	20.0	19.0	18.5				
11-6	22.0	20.0	19.0	18.0	19.0	19.0	19.0	19.0
11-13								
12-2	18.5	15.0	13.5	13.0	14.5	14.0	14.0	14.0
12-6	18.2	17.0	15.5	14.5				
Mean	20.2	18.0	16.8	16.0	16.8	16.5	16.5	16.0
S.D.[1]	2.11	2.45	2.72	2.68	3.18	3.54	3.54	2.83
C.V.[2]	10.4%	13.6%	16.2%	16.7%	18.9%	21.4%	21.4%	17.7%

[1] Standard Deviation

[2] Coefficient of Variation

TABLE B-2

pH Levels in the Pond System

Date 1969	Sampling Point				Depth Profile at Sampling Pt. 3A Sampling Depth (feet)			
	2	3	4	5	Surface	1.0	2.0	3.0
10-23								
10-30	7.7	7.8	8.0	7.9				
11-6	7.8	7.7	7.8	7.8	7.9	7.8	7.8	7.8
11-13								
12-2	7.5	7.5	7.6	7.5	7.5	7.5	7.5	7.5
12-6	7.8	7.8	7.8	7.8				
Mean	7.7	7.7	7.8	7.8	7.7	7.6	7.6	7.6
S.D.	0.14	0.14	0.16	0.17	0.28	0.21	0.21	0.21
C.V.	1.8%	1.8%	2.1%	2.2%	3.7%	2.8%	2.8%	2.8%

TABLE B-3

Total Nitrogen Concentrations
(all values mg/1)

Date 1969	Sampling Point				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	28.0	30.8	31.5	28.7					
10-30	26.3	29.0	28.8	29.0					
11 6	25.7	29.3	29.0	28.7					
11-13									
12-2	24.3	27.1	27.1	28.0	28.5	28.7	28.3	28.1	28.7
12-6	23.8	27.2	29.1	28.6					
Mean	25.61	28.6	29.1	28.6	28.5	28.7	28.3	28.1	28.7
S.D.	1.67	1.55	1.57	0.37					
C.V.	6.5%	5.4%	5.4%	1.3%					

TABLE B-4

Ammonia-N Concentrations
(all values mg/1)

Date 1969	Sampling Point				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	19.0	21.8	21.3	20.7					
10-30	19.6	21.1	21.3	21.5					
11-6	20.6	25.3	28.0	23.8					
11-3									
12-2	22.8	26.3	27.0	26.1	25.8	26.5	23.7	27.0	26.8
12-6									
Mean	20.5	23.6	24.4	23.03	25.8	26.5	23.7	27.0	26.8
S.D.	1.67	2.56	3.60	2.43					
C.V.	8.1%	10.8%	14.7%	10.6%					

TABLE B-5

Phosphate-P Concentrations
(all values in mg/l)

Date 1969	Sampling Point				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	8.7	10.1	11.1	11.0					
10-30	9.9	11.1	11.5	12.1					
11-6	8.4	10.6	11.9	12.2					
11-31									
12-2	15.0	15.4	13.2	14.3	16.0	14.4	15.2	12.5	13.9
12-6	12.3	13.1	13.4	14.8					
Mean	10.86	12.06	12.22	12.88	16.0	14.4	15.2	12.5	13.9
S.D.	2.78	2.19	1.03	1.60					
C.V.	25.6%	18.1%	8.4%	12.5%					

TABLE B-6

Total Suspended Solids Concentration (all values in mg/1)

Date 1969	Sampling Point				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	40.4	50.0	63.4	6[illegible].8					
10-30	33.0	39.6	44.2	5[illegible].0					
11-6	40.8	31.0	31.5	2[illegible].6	26.6	32.4	26.4	85.6	--
11-13									
12-2	37.9	35.0	50.2	2[illegible].9	30.5	35.5	30.7	34.7	37.3
12-6	34.2	38.2	37.3	3[illegible].8					
Mean	39.06	38.76	45.32	4[illegible].6	28.6	34.0	28.5	60.2	37.3
S.D.	6.55	7.10	12.32	1[illegible].9	2.76	2.19	2.90	36.0	--
C.V.	16.8%	18.3%	27.2%	3[illegible].2%	9.6%	6.4%	10.2%	59.8%	--

TABLE B-7

Volatile Suspended Solids Concentrations
(all values in mg/l)

Date 1969	Sampling Point				Depth Profile at Sampling Ppoint 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	44.0	45.0	55.2	59.0					
10-30	30.8	39.6	44.2	55.0					
11-6	37.6	28.7	29.7	29.0	24.8	29.0	24.4	69.2	
11-13									
12-2	34.2	32.1	50.2	24.0	28.6	28.6	27.8	30.2	33.6
12-6	26.8	30.9	30.2	31.3					
Mean	34.68	35.26	41.90	39.66	26.7	28.8	26.1	49.7	33.6
S.D.	6.57	6.81	11.58	16.11	2.69	0.28	2.4	27.5	--
C.V.	19.0%	19.3%	27.6%	40.6%	10.0%	1.0%	9.2%	55.5%	--

TABLE B-8

Dissolved Inorganic Carbon Concentrations
(all values in mg/1)

Date 1969	Sampling Poing				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23	--	--	--	--					
10-30									
11-6									
11-13									
12-2	32.0	36.0	1.0	21.0	29.0	29.0	43.0	29.0	14.0
12-6	52.0	55.0	52.0	54.0					
Mean	42.0	45.5	26.5	37.5	29.0	29.0	43.0	29.0	14.0
S.D.	14.1	13.4	36.0	23.3					
C.V.	33.7%	29.5%	136.1%	62.2%					

TABLE B-9

Dissolved Organic Carbon Concentrations
(all values in mg/1)

Date 1969	Sampling Points				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23									
10-30									
11-6									
11-13									
12-2	21.0	20.0	12.0	16.0	22.0	16.0	18.0	19.0	18.0
12-6	24.0	21.0	27.0	23.0					
Mean	22.5	20.5	19.5	19.5	22.0	16.0	18.0	19.0	18.0
S.D.	2.12	0.71	10.61	4.95					
C.V.	9.4%	3.4%	54.4%	25.4%					

TABLE B-10

Inorganic Carbon of the Suspended Solids Fraction
(all values in mg/1)

Date 1969	Sampling Point				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23									
10-30									
11-6									
11-13									
12-2	10.0	8.0	2.0	3.0	8.0	13.0	3.0	12.0	4.0
12-6	1.0	3.0	6.0	4.0					
Mean	5.5	5.5	4.0	3.5	8.0	13.0	3.0	12.0	4.0
S.D.	6.36	3.53	2.83	0.71					
C.V.	115.0%	64.0%	70.7%	20.2%					

TABLE B-11

Organic Carbon of the Suspended Solid Fraction
(all values in mg/l)

Date 1969	Sampling Points				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23									
10-30									
11-6									
11-13									
12-2	19.0	22.0	28.0	18.0	22.0	23.0	23.0	27.0	25.0
12-6	11.0	11.0	13.0	17.0					
Mean	15.0	16.5	20.5	17.5	22.0	23.0	23.0	27.0	25.0
S.D.	5.65	7.78	10.6	0.71					
C.V.	37.7%	47.1%	51.7%	4.0%					

TABLE B-12

Total Carbon Concentrations
(all values in mg/1)

Date 1969	Sampling Points				Depth Profile at Sampling Point 3A Sampling Depth (feet)				
	2	3	4	5	Surface	1.0	2.0	3.0	3.5
10-23									
10-30									
11-6									
11-13									
12-2	82.0	86.0	43.0	58.0	81.0	81.0	87.0	87.0	61.0
12-6	88.0	90.0	98.0	98.0					
Mean	85.0	88.0	70.5	78.0	81.0	81.0	87.0	87.0	61.0
S.D.	4.24	2.83	38.89	28.28					
C.V.	5.0%	3.2%	55.1%	36.3%					

TABLE B-13

Chemical Oxygen Demand in the Pond System
(all values in mg/1)

Date 1969	Sampling Points			
	2	3	4	5
10-23				
10-30	122.0	131.0	131.0	119.0
11-6	117.0	117.0	108.0	108.0
11-13				
12-2				
12-6				
Mean	119.5	124.0	119.5	113.5
S.D.	3.53	9.0	16.26	7.78
C.V.	3.0%	8.0%	13.6%	6.85%

TABLE C-1

Monthly Means of pH, Temperature, and Dissolved Oxygen in the Anaerobic Pond - Sampling Point 2

Date	pH	Temperature (^{o}C)	Dissolved Oxygen (mg/1)
1969 March	6.9	14.5	6.0
April	7.2	18.3	6.6
May	7.2	20.8	4.0
June	7.3	21.5	3.5
July	7.0	24.0	2.2
Aug.	7.2	23.5	1.8
Sep.	6.8	22.8	0.5
Oct.	6.8	16.8	--
Nov.	6.8	13.8	--
Dec.	7.1	12.0	--
1970 Jan.	6.3	13.4	--
Feb.	6.6	13.2	--
Mean	6.93	17.88	3.51
S.D.	0.29	4.48	2.22
C.V.	4.2%	25.0%	63.4%

TABLE C-2

Monthly Means of pH, Temperature, and Dissolved Oxygen in the High-Rate Pond - Sampling Pt. 3

Date	pH	Temperature (°C)	Dissolved Oxygen (mg/1)
1969 March	7.6	14.5	8.4
April	8.2	17.9	10.6
May	8.1	19.9	7.8
June	7.9	21.0	6.0
July	--	23.2	3.6
Aug.	7.9	22.8	4.8
Sep.	7.8	21.2	3.4
Oct.	7.8	16.8	--
Nov.	7.0	11.0	--
Dec.	7.0	12.5	--
1970 Jan.	6.6	13.4	--
Feb.	6.4	12.6	--
Mean	7.48	17.23	6.37
S.D.	0.62	4.36	2.68
C.V.	8.3%	25.3%	42.1%

TABLE C-3

Monthly Means of pH, Temperature, and Dissolved Oxygen in the Settling Pond - Sampling Point 4

Date	pH	Temperature (^{o}C)	Dissolved Oxygen (mg/1)
1969			
March	8.3	14.0	10.6
April	9.2	17.9	11.6
May	9.6	19.6	917
June	8.2	21.2	6.2
July	7.5	23.8	4.1
Aug.	8.2	23.0	5.3
Sep.	9.2	21.5	3.3
Oct.	7.8	16.5	--
Nov.	7.5	13.5	--
Dec.	7.6	12.0	--
1970			
Jan	7.2	12.8	--
Feb.	7.2	13.0	--
Mean	8.12	17.40	7.56
S.D.	0.82	4.33	3.33
C.V.	10.1%	24.9%	44.1%

TABLE C-4

Monthly Means of pH, Temperature and Dissolved Oxygen in Polishing Pond I - Sampling Point 5

Month	pH	Temperature (°C)	Dissolved Oxygen (mg/1)
1969 March	8.6	15.0	12.3
April	8.9	17.8	10.0
May	9.1	20.0	9.6
June	8.7	21.5	10.4
July	8.9	24.0	7.0
Aug.	8.4	23.5	5.8
Sep.	9.2	22.5	7.2
Oct.	8.6	16.8	7.0
Nov.	8.4	13.8	6.7
Dec.	7.8	12.0	7.0
1970 Jan	7.4	12.5	6.2
Feb.	7.1	12.8	6.5
Mean	8.42	15.81	7.98
S.D.	0.66	6.54	2.06
C.V.	7.9%	41.4%	25.8%

TABLE C-5

Monthly Means of pH, Temperature, and Dissolved Oxygen in Polishing Pond II - Sampling Point 6

Month	pH	Temperature (°C)	Dissolved Oxygen (mg/1)
1969 March	8.0	15.0	10.1
April	7.8	17.9	9.1
May	8.6	19.1	9.0
June	Dry	Dry	Dry
July	"	"	"
Aug.	"	"	"
Sep.	"	"	"
Oct.	"	"	"
Nov.	"	"	"
Dec.	7.5	12.0	6.2
1970 Jan.	7.7	11.6	7.8
Feb.	7.2	13.0	7.8
Mean	7.80	14.77	8.33
S.D.	0.48	3.14	4.31
C.V.	6.1%	21.3%	51.7%

Table C-6

Water Temperature (°C) Readings in the Pond System

Date 1970	Sampling Point						Depth Profile at Sampling Pt.3A			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16										
3-30		17.0	17.3	16.o	16.3	18.0	--	17.3	17.0	17.0
4-6		18.0	19.0	18.0	17.7	19.0	18.9	18.1	18.3	18.1
4-15		15.6	15.0	15.7	16.0	16.0				
4-20										
4-29		17.3	17.5	17.6	17.5	17.8				
Mean		17.0	17.2	16.9	16.9	17.7[1]	18.9	17.7	17.6	17.6
S.D.		1.02	1.65	1.12	0.85	1.25	--	0.56	0.92	0.78
C.V.		6.0%	9.6%	6.6%	5.0%	7.1%	--	3.2%	5.2%	4.4%

[1] Higher temperature because of shallow shore sample.

TABLE C-7

Secchi Disk Readings in Centimeter

Date 1970	Sampling Points					
	1	2	3	4	5	6
3-16		32	24	33	110	
3-30		29	25	33	100	
4-6		25	26	42	120	
4-15		20	20	48	69	
4-20		21	23	52	89	
M						
Mean		25.4	23.6	41.6	97.6	
S.D.		5.13	2.30	8.6	19.7	
C.V.		20.2%	9.8%	20.7%	20.2%	

TABLE C-8

pH Levels in the Pond System

Date 1970	Sampling Point						Depth Profile at Sampling Pt. 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16		7.4	7.6	8.8	6.9	7.2				
3-30	7.1	8.0	8.65	8.65	6.9	7.25	--	8.30	--	8.20
4-6		7.9	8.3	9.4	8.25	8.25	8.15	8.10	8.10	8.10
4-15		7.55	8.2	7.35	7.65	7.45				
4-20										
4-29	7.25	7.45	7.85	7.15	7.40	7.30				
Mean	7.18	7.66	8.12	8.27	7.42	7.49	8.15	8.20	8.10	8.15
S.D.	0.11	0.27	0.41	0.98	0.57	0.19		0.14		0.07
C.V.	1.5%	3.6%	5.0%	11.8%	7.6%	2.5%		1.7%		0.9%

TABLE C-9

Total Suspended Solids Concentrations
(all values in mg/1)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16	--	51.3	69.4	36.1	2.2	24.3				
3-30	174.2	39.5	52.2	33.2	26.0	21.4	--	65.0	54.6	66.0
4-6	--	47.3	44.6	19.2	6.0	12.4	43.4	52.3	44.5	47.2
4-15	--	49.7	55.2	11.3	3.6	2.8				
4-20										
4-29	124.2	83.2	59.2	25.1	14.2	33.3				
Mean	149.2	54.2	56.1	25.0	10.4	18.8	43.4	58.6	49.6	56.6
S.D.	35.35	16.83	9.14	10.14	9.89	11.67		8.98	7.14	13.29
C.V.	23.7%	31.1%	16.3%	40.6%	95.0%	62.0%		15.3%	14.4%	23.5%

TABLE C-10

Volatile Suspended Solids Concentrations
(all values in mg/l)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16		41.8	50.4	26.9	1.7	3.4				
3-30		--	42.2	27.8	3.4	2.2	--	51.4	42.6	48.2
4-6		43.1	33.0	15.1	3.7	4.2	33.3	37.6	34.4	35.0
4-15		45.5	47.4	7.2	1.8	1.3				
4-20										
4-29	110.4	83.2	55.6	16.1	5.4	7.6				
Mean	110.4	53.4	45.7	18.6	3.2	3.7	33.3	44.5	38.5	41.6
S.D.		19.93	8.61	8.69	1.53	2.4		9.76	5.80	9.33
C.V.		37.3%	18.8%	46.7%	47.7%	65.6%		21.9%	15.1%	22.4%

TABLE C-11

Phosphate (PO_4) Concentrations
(all values in mg/1)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16	--	5.68	5.34	4.57	4.05	3.95				
3-30	11.8	7.06	5.74	4.91	4.30	4.15	--	6.51	6.14	6.20
4-60	--	8.0	6.8	5.1	4.3	3.9	7.1	7.20	7.60	7.60
4-15	--	9.33	8.81	7.21	4.94	4.71				
4-20										
4-29										
Mean	11.8	7.52	6.67	5.45	4.40	4.18	7.10	6.86	6.87	6.90
S.D.	--	1.54	1.55	1.20	0.38	0.37		0.49	1.03	0.99
C.V.	--	20.5%	23.3%	21.9%	8.6%	8.8%		7.1%	15.0%	14.3%

TABLE C-12

Total Nitrogen Concentrations[1]
(all values in mg/l)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16		12.1	11.1	6.5	3.7	2.2				
3-30	31.7	10.5	8.1	6.7	5.7	4.4	--	12.4	6.5	9.2
4-6		11.9	7.8	4.0	5.0	3.1	7.1	8.2	6.6	8.7
4-15										
4-20										
4-29	39.2	--	11.1	9.1	5.4	2.8				
Mean	35.4	11.50	9.5	6.6	5.0	3.1	7.1	10.3	6.6	9.0
S.D.	5.30		1.82	2.08	0.88	0.86	--	2.97	0.07	0.35
C.V.	15.%		19.2%	31.6%	17.6%	27.8%	--	28.8%	1.0%	3.9%

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[1] Excluding nitrite and nitrate

TABLE C-13

Ammonia-N Concentrations
(all values in mg/l)

Date 1970	Sampling Points					
	1	2	3	4	5	6
3-16						
3-30						
4-6						
4-15						
4-20	--	7.42	5.6	3.02	3.64	0.42
4-29	25.6	8.00	6.2	7.10	3.60	1.10
Mean	25.6	7.71	5.9	5.1	3.62	0.76
S.D.		0.41	0.42	2.88	0.03	0.48
C.V.		5.3%	7.2%	56.5%	0.8%	63.2%

TABLE C-14

Total Alkalinity Concentrations (as $CaCO_3$)
(all values in mg/l)

Date 1970	Samplint Points						Depth Profile at Sampling Pt. 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16	--	108.0	101.0	93.0	84.0	70.0				
3-30	158.2	107.8	92.2	94.2	82.6	70.0	--	102.2	82.2	96.8
4-6		103.8	104.4	93.8	95.4	75.2	108.6	108.2	107.0	109.8
Mean	158.2	106.5	99.2	93.7	87.3	71.7	108.6	105.2	94.6	103.3
S.D.		2.37	6.30	0.61	7.0	3.0		4.24	17.5	9.19
C.V.		2.2%	6.3%	8.0%	4.2%			4.0%	18.5%	8.9%

TABLE C-15

Biological Oxygen Demand[1]
(all values in mg/1)

Date 1970	Samplint Points					
	1	2	3	4	5	6
3-16						
3-30	179.0	20.3				
4-6						
4-15	--	18.8	13.9	5.4	2.5	4.3
4-20	--	23.8[2] 8.1	5.8	6.5	3.9	5.1
4-29	106.0	17.8 0.5[2]	5.0	3.3	0.0	2.2
Mean	142.5	20.2	8.2	5.1	2.1	3.9
S.D.	51.62	2.63	4.92	1.62	1.98	1.50
C.V.	36.2%	13.0%	60.0%	31.9%	94.0%	38.5%

[1] For filtered pond liquid fraction

[2] For solid fraction

TABLE C-16

Chemical Oxygen Demand[1]
(all values in mg/l)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16										
3-30	367.0	99.0								
4-6	--	114.0	87.0	51.0	25.0	27.0	75.0	88.0	80.0	76.0
4-15	--	113.0 45.9[2]	51.6	34.0	25.2	23.9				
4-20										
4-29	247.0	137.0 32.0[2]	44.0	32.0	18.0	14.0				
Mean	307.0	115.8	60.9	39.0	22.7	21.6	75.0	88.0	80.0	76.0
S.D.	84.85	15.73	22.95	10.44	4.10	6.79				
C.V.	27.6%	13.6%	37.9%	26.8%	18.1%	31.4%				

[1] For filtered pond liquid fraction

[2] For solid fraction

TABLE C-17

Total Carbon Concentrations (all values in mg/1)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16										
3-30	131.5	59.7	42.0	38.0	33.0	27.5	--	47.0	39.0	43.0
4-6	--	67.0	60.1	47.3	36.5	28.5				
4-15										
4-20										
4-29										
Mean	131.5	63.4	51.0	42.6	34.8	28.0	--	47.0	39.5	43.0
S.D.		5.16	12.80	6.58	2.48	0.7				
C.V.		8.1%	25.1%	15.4%	7.1%	2.5%				

TABLE C-18

Dissolved Inorganic Carbon Concentrations
(all values in mg/1)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16										
3-30	43.0	30.8	26.0	27.5	23.5	21.0	--	30.0	24.5	28.5
4-6	--	36.0	33.0	28.0	29.0	24.0				
4-15										
4-20										
Mean	43.0	33.4	29.5	27.8	26.2	22.5	--	30.0	24.5	28.5
S.D.		3.68	4.95	0.35	3.89	2.12				
C.V.		11.0%	16.8%	1.3%	14.8%	9.4%				

TABLE C-19

Dissolved Organic Carbon Concentrations
(all values in mg/1)

Date 1970	Sampling Points						Depth Profile at Sampling Point 3A Sampling Depth (feet)			
	1	2	3	4	5	6	Surface	1.0	2.0	3.0
3-16										
3-30	14.5	13.7	16.0	10.5	9.5	6.5	--	17.0	15.0	15.0
4-6	--	17.5	15.5	12.5	7.5	4.5				
4-15										
4-20										
Mean	14.5	15.6	15.8	11.5	8.5	5.5	--	17.0	15.0	15.0
S.D.		2.69	0.35	1.41	1.41	1.41				
C.V.		17.2%	2.2%	12.3%	16.6%	25.7%				

TABLE C-20

pH Levels of Flask Cultures Grown in Pond Liquid
Under Artificial and Natural Light

Media	Natural Light					Light Box				
	4-10	4-11	4-12	4-13	4-14	4-10	4-11	4-12	4-13	4-14
Control	7.90	8.40	8.60	8.90	9.15	8.45	9.10	9.55	9.95	9.90
$NaHCO_3$	9.00	9.10	9.15	9.25	9.35	9.05	9.30	9.65	9.95	9.95
KNO_3	8.50	8.55	8.90	9.25	9.55	8.40	8.95	9.90	10.35	10.30
KH_2PO_4	7.10	7.05	6.95	6.90	6.80	7.10	7.05	7.05	7.00	6.95
Fe Versonel	8.15	8.45	8.65	8.95	9.15	8.45	9.10	9.95	10.30	10.10
Micronutrients	8.15	8.20	8.55	8.70	8.85	8.60	8.85	9.55	10.35	10.30

TABLE C-21

Formula of the Modified Arnon's Micronutrient Stock Solution (53)

Nutrient	Molar Concentration in Media moles/liter	Preparation g/ liter in stock solution
H_3BO_3	4.6×10^{-5}	2.86
$MnCl_2 \cdot 4H_2O$	9.2×10^{-7}	1.81
$ZnSO_4 \cdot 7H_2O$	7.7×10^{-7}	0.222
$CuSO_4 \cdot 5H_2O$	3.2×10^{-7}	0.079
MoO_3 (99.5%)	1.0×10^{-7}	0.015
$CoCl_2 \cdot 6H_2O$	1.7×10^{-7}	0.040

TABLE D-1

Analyses for November 8, 1970 Samples

Sampling Point	Temp. °C	pH	Total Sus. Solids mg/l	Total Sus. Solids mg/l	Chlorophyll mg/l
Concord 3	20.3	7.30	28.5	27.3	0.038
Concord 4	18.5	7.30	27.8	24.6	0.226
Concord 5	17.8	7.45	21.7	19.5	0.219
Saint Helena 3	16.2	7.20	97.4	88.0	3.05
Saint Helena 4	16.1	8.45	143.2	143.2	2.92
Saint Helena 5	16.0	7.95	49.0	37.8	0.75

TABLE D-2

Analyses for November 8, 1970 Samples
(values except ratios in mg/l)

Sampling Point	Total C	Total N	NH_3	PO_4	C/N
Saint Helena 3	27	13.4	10.3	14.8	2.1
Saint Helena 4	24	8.6	5.6	16.3	2.8
Saint Helena 5	23	2.2	0.0	11.7	10.4
Concord 3	45	26.0	22.0	13.8	1.7
Concord 4	95	29.6	24.4	13.4	3.3
Concord 5	69	28.3	24.5	14.3	2.4

TABLE D-3

C/N Ratios and pH Levels at Start of Ancillary Light-Box Studies

Sampling Point	C/N	pH
Saint Helena 3		
3 flasks (control)	2.1	7.7
3 flasks	8.0	7.7
3 flasks	8.0	9.8
Saint Helena 4		
3 flasks (control	2.8	7.8
3 flasks	8.0	7.8
3 flasks	8.0	9.5
Concord 5		
3 flasks (control	2.4	7.7
3 flasks	8.0	7.7
3 flasks	8.0	9.9
Saint Helena 5		
3 flasks (control	10.2	7.8
3 flasks	8.0	7.8

TABLE D-4

Final Concentrations of Suspended Solids and Chlorophyl for Sampling Point - Saint Helena 3 (Sampling run from 11-10 to 11-23)

Constituent	Control[1] pH 7.7 Final mg/l	Adjusted Sample[1] (C/N 8) (pH 7.7) Final mg/l	vs. Control mg/l	%	Adjusted Sample[1] (C/N 8) (pH 9.8) Final mg/l	vs. Control mg/l	%	Mean of Adjusted Samples Vs. Control mg/l	%
Tot. Sus. Solids mg/l	185.1	285.3	100.2	+54.1	274.3	+89.2	+48.2	+94.7	+51.2
Vol. Sus. Solids mg/l	131.9	228.3	+96.4	+73.0	213.2	+81.3	+61.6	+88.9	+67.3
Fixed Sus. Solids mg/l	53.2	57.1	+ 3.9	+ 7.3	61.1	+ 7.9	+14.8	+ 5.9	+11.0
Chlorophyl mg/l	0.91	2.56	+1.65	+180.5	1.49	+0.58	+63.2	+1.12	+121.9

[1] Mean for three flasks

[2] Mean for six flasks

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TABLE D-5

Final Concentrations of Suspended Solids and Chlorophyl for Sampling Point - Saint Helena 4 (Sampling run from 11-10 to 11-23)

Constituent	Control[1] pH 7.8	Adjusted Sample[1] (C/N 8) (pH 7.8)			Adjusted Sample[1] (C/N 8) (pH 9.5)			Mean of Adjusted Samples	
	Final mg/1	Final mg/1	Vs. Control mg/1	Vs. Control %	Final mg/1	Vs. Control mg/1	Vs. Control %	Vs. Control mg/1	Vs. Control %
Tot. Sus. Solids mg/1	179.3	172.8	- 6.5	- 3.6	222.1	+42.8	+23.9	+18.2	+10.2
Vol. Sus. Solids mg/1	126.0	134.8	+ 8.8	+ 7.0	161.7	+35.7	+28.3	+22.3	+17.7
Fixed Sus. Solids mg/1	53.3	38.0	-15.3	-28.7	60.4	+ 7.1	+13.3	- 4.1	- 7.7
Chlorophyl mg/1	0.43	0.67	+0.24	+55.8	1.46	+1.03	+237.7	+0.64	+146.7

[1] Mean for three flasks

[2] Mean for six flasks

TABLE D-6

Final Concentrations of Suspended Solids and Chlorophyl for Sampling Point - Saint Helena 5 (Sampling run from 11-10 to 11-23)

Constituent	Control[1] pH 7.7 Final mg/l	Adjusted Sample[1] (C/N 8) Final mg/l	Vs. Control mg/l	%
Tot. Sus. Solids mg/l	67.4	85.5	+18.1	+26.8
Tot. Vol. Solids mg/l	59.7	71.5	+11.8	+19.8
Fixed Solids mg/l	7.7	14.0	+ 6.3	+81.8
Chlorophyl mg/l	0.17	0.23	+0.06	+35.5

[1] Mean for three flasks

TABLE D-7

Final Concentrations of Suspended Solids and Chlorophyl
for Sampling Point - Concord 5
(Sampling run from 11-10 to 11-23)

Constituent	Control[1] pH 7.7	Adjusted Sample[1] (C/N 8) (pH 7.7)			Adjusted Sample[1] (C/N 8) (pH 9.9)			Mean of Adjusted Samples[2]	
	Final mg/l	Final mg/l	vs. Control mg/l	vs. Control %	Final mg/l	vs. Control mg/l	vs. Control %	Vs. Control mg/l	Vs. Control %
Tot. Sus. Solids mg/l	338.1	473.5	+135.4	+40.0	494.8	+156.7	+46.3	+146.0	+43.2
Vol. Sus. Solids mg/l	200.9	311.1	+110.2	+54.9	329.2	+128.3	+63.9	+119.3	+59.4
Fixed Sus. Solids mg/l	137.2	162.4	+ 25.2	+18.4	158.9	+ 21.7	+15.8	+ 24.0	+17.1
Chlorophyl mg/l	2.86	4.08	+ 1.22	+42.6	2.30	- 0.56	-19.8	+ 0.66	+11.4

[1] Mean for three flasks

[2] Mean for six flasks

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